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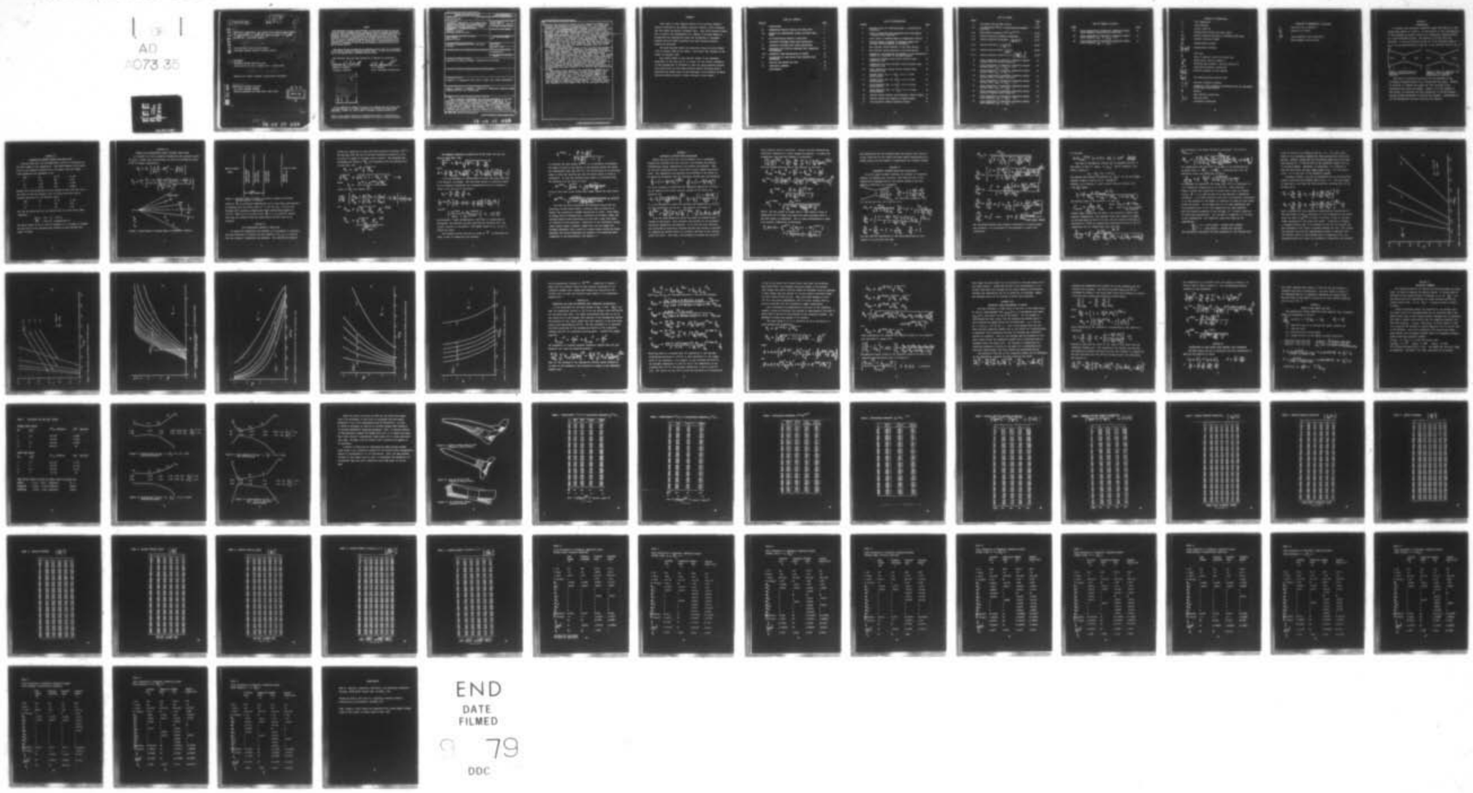

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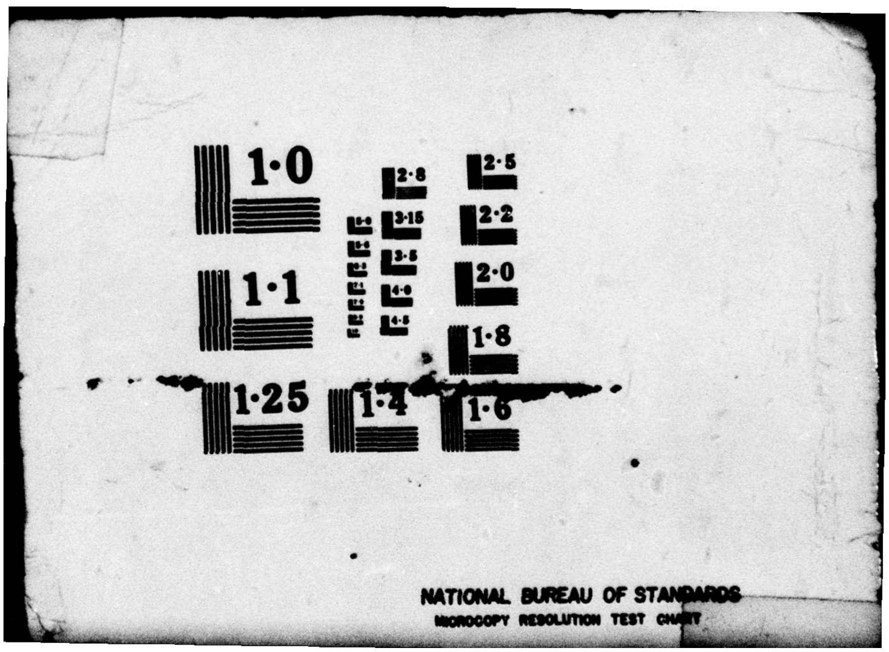
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SUPERSONIC COMBUSTION, AIR DISSOCIATION THROUGH SHOCK WAVES AND AERODYNAMICS OF CHEMICALLY REACTING GASES IN A PLANAR CONVERGING - DIVERGING NOZZLE.

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Dennis W. Schroll — C. R. Carroll

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Much research ~~and testing~~ has been accomplished in the past years to develope a supersonic ramjet engine. The topic is discussed in almost all propulsion texts. However, very little headway has been made in theoretical design techniques as many of the standard computational methods used for ramjet subsonic combustion do not apply. For instance, it is possible to use a constant area nozzle for subsonic combustion in a ramjet as heat

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addition and frictional effects in the combustion chamber will decrease the pressure and accelerate the flow. For supersonic combustion the velocity decreases tending to choke the flow. To overcome this ~~difficulty~~ area increase in the combustion zone is ~~are~~ used. ~~The analysis assumes~~ a strong normal shock on the diffuser inlet for free stream mach numbers of 5 and 10 and the ~~analysis also considers~~ shock free flow of these mach numbers are assumed. Accompanied with the strong normal shock are large stagnation pressure losses in the diffuser inlet, meaning the diffuser inlet will act as a flat plate to oncoming airflow. For this reason, it would be best to provide air spillage and not use too large an inlet. For the shock expelled case, the drag through the engine would be less, but static pressure rises up to 272 atmospheres are calculated.

Basic assumptions that apply to the computational schemes in this paper are the quantum mechanical relationships developed by statistical mechanics. This means the assumption of equilibrium must apply within the zones of the engine calculated. This is a most valid assumption for high speed flow. High energy molecules will have time to reach equilibrium values along each section of the engine, but have little time to dissipate to the walls of the engine. The inviscid assumption is then valid. Of course, chemical reactions within the combustion chamber are not so simple in nature as applied here, but the constant pressure assumption allows chemically reacting computations to be determined and then compared to the perfect gas computational scheme.

The final Thrust Specific Fuel Comsumption ~~(TSFC)~~ values are sufficiently high to warrant further investigation into supersonic combustion as a method of propulsion. They are slightly higher than that of a designed ramjet which is in operation with hydrocarbon fuels. At these very high speeds, it is possible to pass a larger amount of air mass per unit time through the supersonic ramjet engine. It's thrust values will therefore be much higher than for the developed ramjets.

FOREWORD

This report is the compiled results of an in-house research project conducted by the author, Dennis W. Schroll, while attending the Ohio State University, Columbus, Ohio. This final research report was to fulfill the requirements for a Master of Science Degree in Aeronautics and Astronautics under the sponsorship of Aerospace Systems Division (DPCD) Long-Term Full-Time Training Contract F3360-75-A-0549-0002.

The work reported herein was performed during the period March 1978 to October 1978 by the author. This report was released by the author in December 1978.

The author wishes to give special thanks to his immediate supervisor at the time, Mr. W. A. Lucka, for his initial nomination to this program and to Professor R. Edse for being research advisor. This study would not have been possible without Professor Edse's equations and tables which he has developed in his research projects that are closely related to those outlined in this report.

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GLOSSARY OF TERMINOLOGY

T	(^oK) temperature
P	(atm) pressure
u	(m/sec) velocity
M	dimensionless frozen flow mach number
η_i	partial pressure fractions of molecules and atoms
$\mathcal{M}$	(g/mole) molecular weight
$\frac{S}{R_2}$	dimensionless entropy
$\left[\frac{h_{f\ abs}}{R_2\ T_2}\right]^T$	dimensionless enthalpy
A	(m^2) area
γ	ratio of specific heats for frozen flow
$n^g_{(i)}$	global molar value of species i
$\mathcal{R}$	universal gas constant = 8314.33 J/K-mole ^oK
$K_p^{(i)}$	equilibrium pressure coefficient
$\left[\frac{H_f}{\mathcal{R}\ T}\right]^T_i$	absolute enthalpy of each species
$\left[\frac{C_p}{\mathcal{R}}\right]_i$	non-dimensionalized specific heat
$h_{f\ abs}^{\ o}$	absolute formation enthalpy
T_o, P_o	stagnation fluid properties determined from the isentropic perfect gas relationships
ρ	density
q	heat addition coefficient
$\nu_{O_2}^{\ o}$	fuel-air ratio
X	correction coefficient

GLOSSARY OF TERMINOLOGY (continued)

X_i	mass fraction of species i
$\dfrac{\mathcal{T}}{\dot{m}_a}$	specific net thrust
TSFC	thrust specific fuel consumption
f	mass weighted fuel-air ratio

SECTION I

INTRODUCTION

A variable area supersonic combustion ramjet was modeled for free stream mach numbers of 5 and 10. It was desired to use a configuration as that proposed in several articles on a hypersonic research vehicle as a joint NASA-USAF project. The problem is divided into four sections: 1) the starting shock at M_∞ =5, 2) the swallowed shock at M_∞ =5, 3) the starting shock at M_∞ =10, 4) the swallowed shock at M_∞ =10.

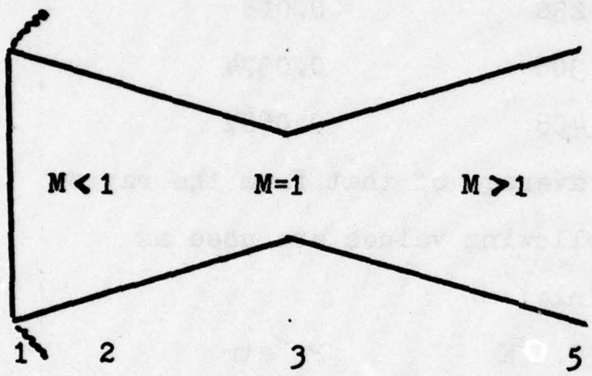


Figure 1. Entrance Shock for Starting Ramjet-Subcritical Condition

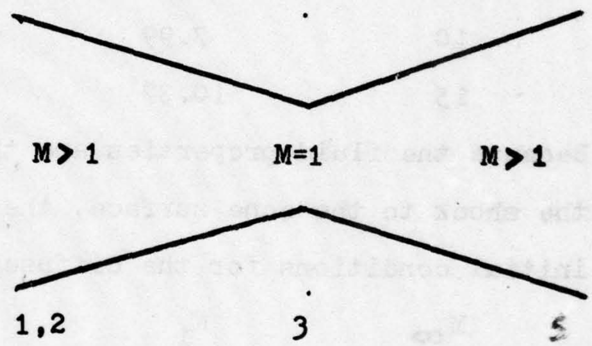


Figure 2. Shock is Swallowed with Supersonic Flow Throughout-Supercritical Condition

The flow is considered non-viscous and the geometry of the converging-diverging channels are 2 dimensional and planar. Effects of curvature to compress and expand the flow uniformly across incremental mach lines are ignored. Rather, it is the purpose of this project to determine the fluid properties at various stations through constant properties of entropy and pressure. Dissociation of air and hydrogen/air chemical reactions are computed.

SECTION II

COMPRESSION THROUGH VEHICLE BOW SHOCK WAVE

The bow shock wave off the hypersonic vehicle is considered as the first stage of air compression. From Taylor-Maccoll cone theory (cone at zero angle-of-attack) with a 7½ degree cone half angle, fluid properties are estimated to be:

M_∞	M_1	T_1 °K	P_1 atm
5	4.51	236	0.018
10	7.99	306	0.0374
15	10.37	408	0.0687

Because the fluid properties are the average of that from the ray on the shock to the cone surface, the following values are used as initial conditions for the diffuser inlet:

M_∞	M_1	T_1 °K	P_1 atm
5	5	230	0.02
10	8	300	0.04

Thus the bow shock wave off the vehicle acts as a mild first stage compressor.

$$\text{AIR IS} \longrightarrow O_2 + 3.76\ N_2$$

$$\mathcal{R} = 8314.33 \text{ Joules/K-mole }^\circ\text{K}$$

The molar volume of air of 3.76 of nitrogen to 1 of oxygen is assumed and the value of the universal gas constant as used through this report is given.

SECTION III

PERFECT GAS COMPUTATIONS ACROSS DIFFUSER INLET SPIKE

To estimate the fluid properties temperature and pressure across the shock, perfect gas relationships are used with decreasing values of γ for higher temperatures.

$$P_2 = P_1 \left[\frac{2\gamma}{\gamma+1} M_1^2 - \frac{\gamma-1}{\gamma+1} \right]$$

$$T_2 = T_1 \left[\frac{\left(1 + \frac{\gamma-1}{2} M_1^2\right)\left(\gamma M_1^2 - \frac{\gamma-1}{2}\right)}{\left(\frac{\gamma+1}{2} M_1\right)^2} \right]$$

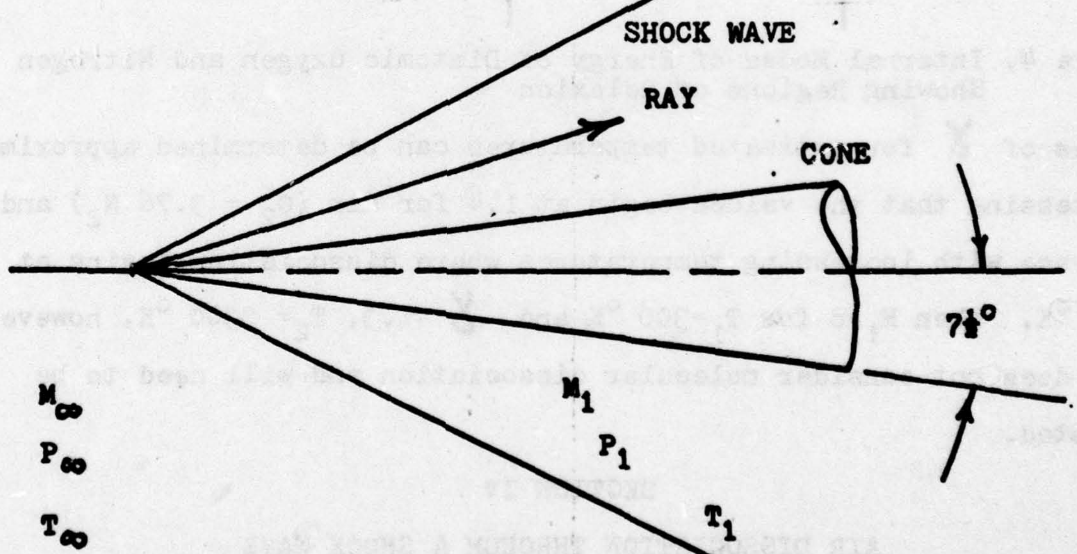


Figure 3. Inlet Spike or Forward Region of Hypersonic Vehicle

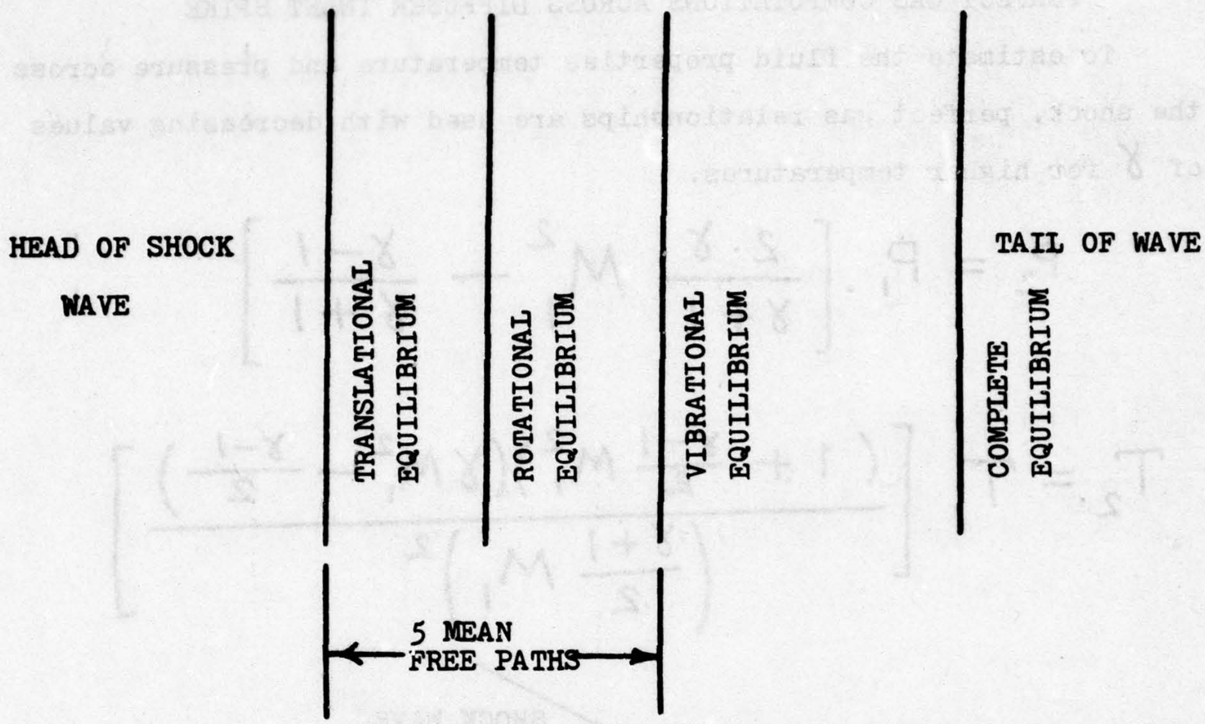


Figure 4. Internal Modes of Energy of Diatomic Oxygen and Nitrogen Showing Regions of Relaxion

Values of γ for estimated temperatures can be determined approximately by guessing that the values begin at 1.4 for air (O_2 + 3.76 N_2) and decrease with increasing temperatures where dissociation begins at 1100 ^oK. When M_1=8 for T_1=300 ^oK and γ =1.3, T_2= 3300 ^oK, however this does not consider molecular dissociation and will need to be adjusted.

SECTION IV

AIR DISSOCIATION THROUGH A SHOCK WAVE

To adjust the temperature and pressure it is necessary to calculate the mole fractions of molecule and atom species of O_2, N_2, O, N and NO from the estimated temperature and pressure. The equilibrium pressure

coefficient equations of each individual reaction is written, ($K^{(i)}$) and the fact that the sum of the mole fractions is equal to 1, and the ratio of oxygen to nitrogen atoms is given. The equations are rearranged and values of η_{O_2} are estimated until the percent error is less than .001.

$$\eta_O = K^{(O)} \sqrt{\eta_{O_2}}$$

$$\sqrt{\eta_{N_2}} = \sqrt{a^2 + 1 - \eta_{O_2} - \eta_O} - a$$

where

$$a = \frac{K^{(N)} + K^{(NO)} \sqrt{\eta_{O_2}}}{2}$$

values of η_{O_2} are assumed until

$$\frac{100}{3.76} \left| \frac{\eta_{N_2} + \frac{1}{2}(\eta_N + \eta_{NO})}{\eta_{O_2} + \frac{1}{2}(\eta_O + \eta_{NO})} - 3.76 \right| = |\Delta| < .001$$

and

$$\eta_{NO} = \sqrt{\eta_{N_2}\, \eta_{O_2}}\; K_P^{(NO)}$$

$$\eta_N = \frac{\sqrt{\eta_{N_2}}\; K_P^{(N)}}{\sqrt{P_{EST}}}$$

The Hugeniot Equation is solved for P_2 EST until the per cent error is less than .01%.

$$\frac{P_2^{CALC}}{P_1} = B + \sqrt{B^2 + \frac{T_2}{T_1} \cdot \frac{m_1}{m_2}}$$

where

$$B = \frac{T_2}{T_1} \cdot \frac{m_1}{m_2} \sum_i n_{i,2} \left(\frac{H_f}{RT}\right)_i^{T_2} - \sum_i n_{i,1} \left(\frac{H_f}{RT}\right)_i^{T_1} - \frac{1}{2}\left(\frac{T_2}{T_1} \cdot \frac{m_1}{m_2} - 1\right)$$

It is now necessary to recalculated the molar fractions each time a new pressure is assumed. Now with these series of equations solved for an estimated temperature and corresponding values of pressure, a value of the velocity is calculated.

$$u_2 = \frac{T_2}{T_1} \cdot \frac{m_1}{m_2} \cdot \frac{P_1}{P_2}\, u_1$$

$$\left[u_1^{CALC}\right]^2 = \left[\left(\frac{P_2}{P_1} - 1\right) \div \left(1 - \frac{T_2}{T_1} \cdot \frac{P_2}{P_1}\right)\right]\left[\frac{T_1 m_2 R}{m_1}\right]$$

until

$$\left| \frac{u_1^{CALC} - u_1^{KNOWN}}{100 \times u_1^{KNOWN}} \right| < .01\%$$

By successive linear extrapolation a new value of temperature is determined, the pressure and mole fractions are adjusted until the correct velocity is calculated. This gives values of T_2, P_2 and u_2 behind the shock.

Now consider frozen flow where a value of γ is determined for these values of temperature and pressure.

$$\gamma^{FROZ} = \frac{\sum_i n_i \left.\frac{c_p}{R}\right)_i^T}{\sum_i n_i \left.\frac{c_p}{R}\right)_i^T - 1}$$

To calculate the mach number (M^{FROZ}), it is necessary to determine the speed of sound in the mixture at the position behind the shock. For temperatures less than 3000 ^{o}K, the contributions of the shifting speed of sound are neglible and only the frozen speed of sound is considered. As such the reference mach number is calculated from the definition of the speed of sound.

$$M^{FROZ} = \frac{u^{CALC}}{w^{FROZ}} = \frac{u^{CALC}}{\sqrt{\gamma^{FROZ} \frac{R}{m} T}}$$

at M_1=8, the value of the frozen mach number behind the inlet shock is

$$M^{FROZ} = \frac{2785}{\sqrt{1.2891 \left(\frac{8314.33}{28.36149}\right) 3.084}} = 0.3413$$

Now that the fluid properties are determined across the non-isentropic strong normal shock, a question might be posed as to whether the condition of assumed equilibrium is valid. Those modes of energy such as translational, rotational for diatomic oxygen and nitrogen usually reach equilibrium in less than 5 mean free paths of collision of the molecules. Relaxation of the vibrational energy state usually takes a somewhat longer time, but for oxygen and nitrogen relaxation still occurs in a narrow region behind the shock. Therefore the frozen properties are assumed to be determined after relaxation or for equilibrium (see Figure 4).

SECTION V

ISENTROPIC DIFFUSER FLOW CALCULTIONS

Behind the shock wave the flow is subsonic and a converging channel will increase the flow velocity, and decrease the molecule translational energy (temperature) and decrese the pressure. That is, the more random molecular motion will be more ordered and directional. The temperature and pressure are estimated at the throat to be values as determined from the isentropic perfect gas relationships

$$\frac{P_0}{P_3} = \left(1 + \frac{\gamma-1}{2} M_3^2\right)^{\gamma/\gamma-1} \qquad \frac{T_0}{T_3} = \left(1 + \frac{\gamma-1}{2} M_3^2\right)$$

It is not necessary to calculate the stagnation properties as ratios can be taken and with sonic velocity assumed at the throat the equations are

$$P_3 = P_2 \left\{\frac{\left(1 + \frac{\gamma-1}{2} M_2^2\right)}{\frac{\gamma+1}{2}}\right\}^{\gamma/\gamma-1} \qquad T_3 = T_2 \left\{\frac{1 + \frac{\gamma-1}{2} M_2^2}{\frac{\gamma+1}{2}}\right\}$$

It is now necessary to adjust the pressure and temperature to account for the dissociation of the air. The equation of entropy is

$$\left.\frac{S}{R_2}\right)^{T_{EST}} = \frac{m_2}{m}\left\{\sum_i n_i \left(\frac{S}{R}\right)^{P=1}_{T_{EST}} - \sum_i n_i \ln n_i - \ln P\right\}$$

With the known properties behind the shock the dimensionless entropy is calculated. Next calculate the entropy for the estimated isentropic temperature and pressure. To do this the mole fractions are calculated as previously outlined and then the entropy is adjusted by changing the pressure until it is within .01% that of the entropy behind the shock. Each time a new pressure is assumed new values of

mole fractions must be calculated. However the mole fractions are relatively insensitive to small changes in pressure. To adjust the temperature, the absolute enthalpy is calculated.

$$\left(\frac{h_{f\,abs}}{R_2 T_2}\right)^{T_{EST}} = \frac{T_{EST}}{T_2}\frac{\mathcal{M}}{\mathcal{M}_i}\sum_i \eta_i \left(\frac{\Delta H_{f\,abs}}{\mathcal{R}\, T}\right)^{T_{EST}}$$

From the energy equation for no fuel addition to the flow,

$$h_{f\,abs}^{\;o} = h_{f\,abs}^{\;T_2} + \frac{u_2^2}{2} = h_{f\,abs}^{\;T_3} + \frac{u_3^2}{2}$$

$$u_3^{CALC} = \left\{\left[\left(\frac{h_{f\,abs}}{R_2 T_2}\right)^{T_2} - \left(\frac{h_{f\,abs}}{R_2 T_2}\right)^{T_3}\right]\frac{2(8314.33)T_2}{\mathcal{M}_2} + u_2^2\right\}^{1/2}$$

$$\gamma_3^{FROZ} = \frac{\sum_i \eta_i \frac{c_p}{\mathcal{R}}\Big)^{T_3\,EST}}{\sum_i \eta_i \frac{c_p}{\mathcal{R}}\Big)^{T_3\,EST} - 1}$$

$$M_3^{FROZ} = \frac{u_3^{CALC}}{\sqrt{\gamma_3^{FROZ}\,\frac{8314.33}{\mathcal{M}_3}\,T_3}}$$

Should the mach number be larger than 1, then choose a value of temperature 100 ^{o}K larger and repeat the above procedure until a new mach number is determined. Now by linear extrapolation a third more accurate temperature is determined.

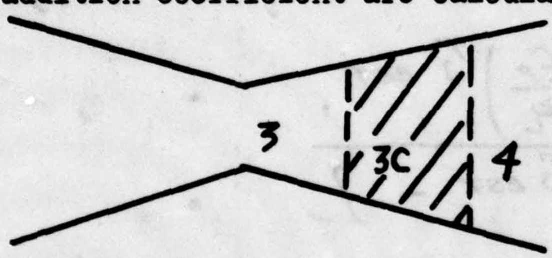
$$T_3\,(est\ 3) = T_3^{est\ 1} + \left[M_3 = 1 - M_3^{est\ 1}\right] \times \left[\frac{T_3^{est\ 2} - T_3^{est\ 1}}{M_3^{est\ 2} - M_3^{est\ 1}}\right]$$

The calculations are now repeated again and usually this value is within 0.1% error as the frozen flow mach number relationship is a fairly linear one with respect to temperature for constant entropy.

SECTION VI

ISENTROPIC DIFFUSER EXIT FLOW CALCULATIONS

To go to region 3C (exit diffuser and entrance of combustion chamber) is somewhat more involved. Heat addition due to the combustion of hydrogen and air for various values of the heat addition coefficient are calculated.



Now

$$\frac{T_{3C}}{T_3} = \frac{1+\frac{\gamma-1}{2}M_3^2}{1+\frac{\gamma-1}{2}M_{3C}^2}$$

for isentropic expansion, from 3 to 3C and for dP=0, du=0 from 3C to 4.

$$M_4 = \frac{M_{3C}}{\sqrt{1+q/c_p T_{3C}}} \qquad \frac{T_{04}}{T_{03C}} = 1 + \frac{q/c_p T_{3C}}{1+\frac{\gamma-1}{2}M_{3C}^2}$$

$$\frac{P_{04}}{P_{03C}} = \left[\frac{1+\frac{\gamma-1}{2}M_{3C}^2\,\frac{1}{1+q/c_p T_{3C}}}{1+\frac{\gamma-1}{2}M_{3C}^2}\right]^{\gamma/\gamma-1}$$

$$\frac{A_4}{A_{3C}} = \frac{T_4}{T_{3C}} = 1 + \frac{q}{c_p T_{3C}} \qquad \frac{P_4}{P_{3C}} = 1$$

The heat addition coefficient is then non-dimensionalized with respect to T_3 and plots are made.

$$M_4 = \frac{M_{3C}}{\sqrt{1 + \frac{q}{C_p T_3}\left[\frac{1 + \frac{\gamma-1}{2} M_{3C}^2}{\frac{1+\gamma}{2}}\right]}}$$

$$\frac{P_{04}}{P_{03C}} = \left[\frac{1 + \frac{\gamma-1}{2} M_{3C}^2 \left\{\frac{1}{1 + \frac{q}{C_p T_3}\left[\frac{1 + \frac{\gamma-1}{2} M_{3C}^2}{\frac{\gamma+1}{2}}\right]}\right\}}{1 + \frac{\gamma-1}{2} M_{3C}^2}\right]^{\frac{\gamma}{\gamma-1}}$$

$$\frac{T_{04}}{T_{03C}} = \frac{1 + \frac{q}{C_p T_3}\left[\frac{1 + \frac{\gamma-1}{2} M_{3C}^2}{\frac{1+\gamma}{2}}\right]}{1 + \frac{\gamma-1}{2} M_{3C}^2}$$

$$\frac{A_4}{A_{3C}} = \frac{T_4}{T_{3C}} = 1 + \frac{q}{C_p T_3}\left[\frac{1 + \frac{\gamma-1}{2} M_{3C}^2}{\frac{1+\gamma}{2}}\right]$$

$$\frac{P_4}{P_{3C}} = 1 \quad \text{where,} \quad q = X \frac{\Delta H_{COMB}^{fuel, T_3}}{m_{fuel\text{-}air\ mix}}$$

The non-dimensionalized heat addition coefficient q is given above. See reference 1 for an outline of the procedure to obtain this coefficient.

For hydrogen

$$\Delta H_{COMB}^{H_2, T_s} = 241.52 \times 10^6 \ \frac{Joules}{K\text{-}mol}$$

The mass of hydrogen-air mixture can be expressed relative to the number of moles of oxygen by $\nu_{O_2}{}^{\circ}$. Before combustion this ratio is given by

$$H_2 + \nu_{O_2}{}^{\circ}\,(O_2 + 3.76\ N_2)$$

The maximum heat release is obtained for $\nu_{O_2}{}^{\circ} = 0.5$ as the oxygen-hydrogen chemical reaction is $H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O$.
However, it is possible to have a leaner fuel-air mixture ratio $\frac{1}{2} \leq \nu_{O_2}{}^{\circ} \leq \infty$.

$$q = \chi \frac{\Delta H_{COMB}^{H_2, T_s}}{m_{H_2} + \nu_{O_2}{}^{\circ}\,(m_{O_2} + 3.76\, m_{N_2})}$$

The specific heat of the mixture, m is given as

$$C_{P,m} = \frac{\gamma_m}{\gamma_m - 1} R_m$$

where $R_m = \mathcal{R} / m_m$

and $\mathcal{R}$ =8314.33 is the Universal Gas Constant

Several ideal assumptions are made in the combustion chamber that expedite computations. The hydrogen enters the combustion chamber at the same speed as that of the air, and its absolute enthalopy is determined at 1000°K for temperatures exceeding this and at the air temperature for air temperatures less than this

$$\frac{q}{C_{P_m} T_3} = \chi \frac{\Delta H_{COMB}^{H_2, T_s}}{\frac{\gamma_m}{\gamma_m - 1}\ \frac{\mathcal{R}}{m_m}\left[m_{H_2} + \nu_{O_2}{}^{\circ}(m_{O_2} + 3.76\, m_{N_2})\right]}$$

Now according to the method outlined in reference 1 the value of $\mathcal{M}_m$ is,

$$\mathcal{M}_m = \frac{4.76\, \nu_{O_2}^{\circ} \dfrac{\mathcal{M}_{H_2}}{\mathcal{M}_{O_2} + 3.76\,\mathcal{M}_{N_2}}}{1 + 4.76\, \nu_{O_2}^{\circ} \dfrac{\mathcal{M}_{O_2} + 3.76\,\mathcal{M}_{N_2}}{\mathcal{M}_1}} \left(\mathcal{M}_{O_2} + 3.76\,\mathcal{M}_{N_2}\right)$$

For temperatures less than 2000 °K the mass of the decelerated air is almost equal to $\mathcal{M}_{O_2} + 3.76\mathcal{M}_{N_2}$. Substituting in all the approprite values and cancelling out gives,

$$\frac{q}{C_{p_m} T_3} = X \frac{\gamma - 1}{\gamma} \frac{29048}{(4.76\, \nu_{O_2}^{\circ} + 1)\, T_3}$$

for hydrogen air mixture γ will range from 1.441 (no combustion) to 1.25 (combustion temperatures up to 3000 °K). Since this non-dimensionalized heat coefficient is mainly used to get an estimate of M_{3C}, γ = 1.4 is used as this is at the position of combustion initiation. A few words should be said about the correction coefficient X, as this pertains to the degree of combustion of gases as they travel across the nozzle. It can range from 0.4 for high temperatures and low pressures up to 1.0 for low temperatures and high pressures. With the possible exception of one case M_∞ = 10, no shock, values of 0.7 would seem satisfactory. For the sake of comparison, 0.7 is used in all computations. Two combustion cases were taken for all computations.

$\nu_{O_2}^{\circ}$ = 0.5 (rich mixture - maximum heat release)

$\nu_{O_2}^{\circ}$ = 2 (lean mixture - minimum heat release)

The procedure to determine the fluid properties at the diffuser exit

3C was to first of all assume we want $M_4 = 1.2$. Too high a mach number in the combustion chamber will mean problems with mixing fuel and air. However, should the flow go subsonic again this would mean flow choking ($M = 1$) and the flow in the combustion chamber will go to low mach numbers. Therefore, in conclusion, it is desired to keep the flow within the mach number range at $M_3 = 1$ at the throat to $M_4 = 1.2$ at the exit of the combustion chamber.

Looking at Figure 3, M_3 can be determined from a calculated heat release coefficient and assumed value of $M_4 = 1.2$. This mach number is then used to calculate the fluid properties isentropically at the diffuser exit.

$$T_{3C} = \frac{T_{3C}}{T_{03C}} \frac{T_{03}}{T_3} T_3 = \frac{\left[1 + \frac{\gamma-1}{2} M_3^2\right]}{\left[1 + \frac{\gamma-1}{2} M_{3C}^2\right]} T_3$$

$$P_{3C} = \frac{P_{3C}}{P_{03C}} \frac{P_{03}}{P_3} P_3 = \left[\frac{1 + \frac{\gamma-1}{2} M_3^2}{1 + \frac{\gamma-1}{2} M_{3C}^2}\right]^{\gamma/\gamma-1} P_3$$

Next, calculate the flow properties considering air dissociation by the same method as used to determine the flow properties at the throat until the value of M_{3C}^{FROZ} is within 0.1% error of that of the mach number determined by the perfect gas method. Inspection of Figures 5 through 10 reveals that it is necessary to add fuel and combust the gas downstream of the throat to prevent choking the flow. Even though the molecular velocity will approximately double in magnitude from the diffuser throat to the diffuser exit for supersonic flow, the expanding nozzle will result in a decrease in temperature and pressure

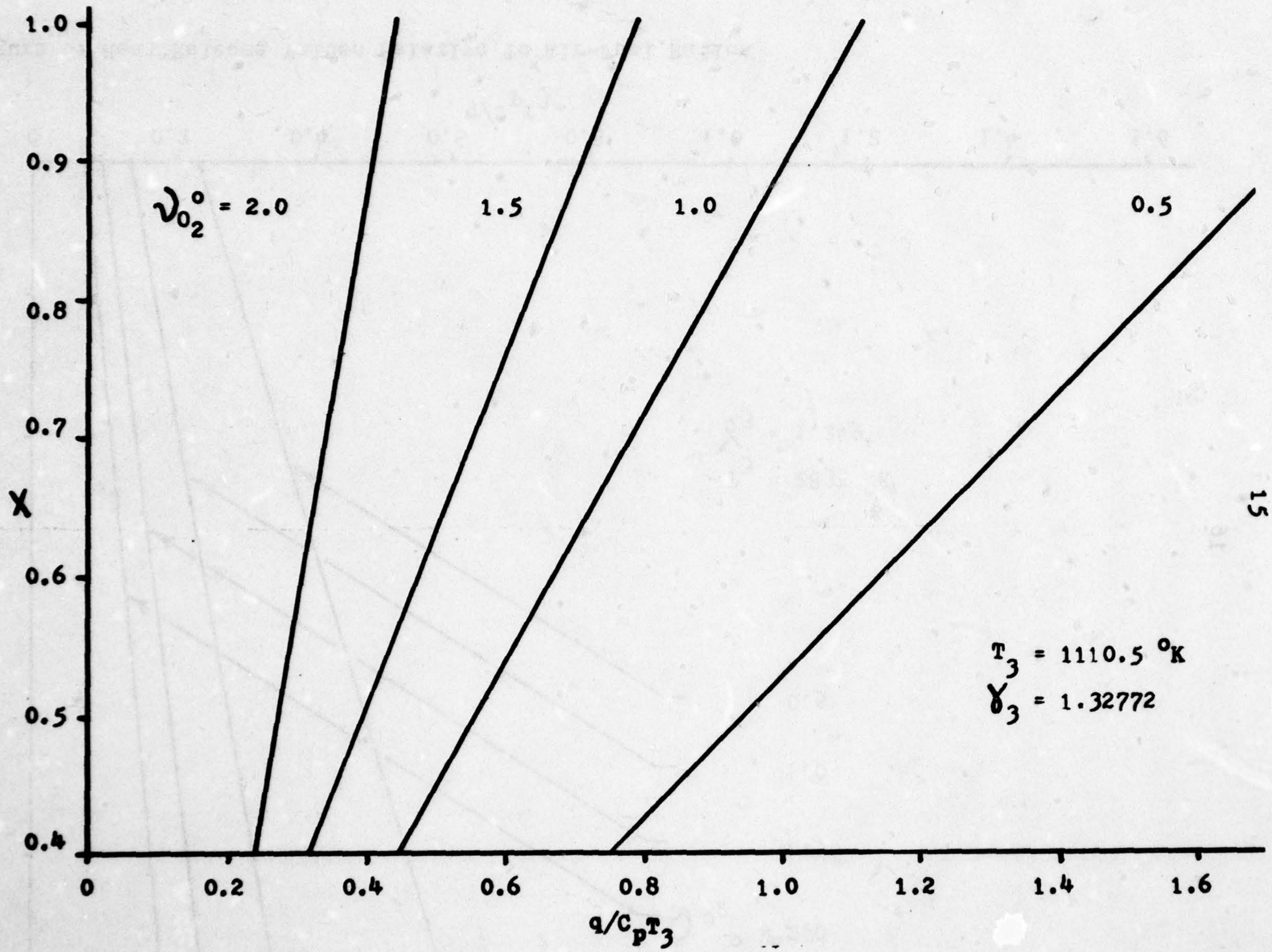


Figure 5. Heat Release Values Relative to Air-Fuel Ratios

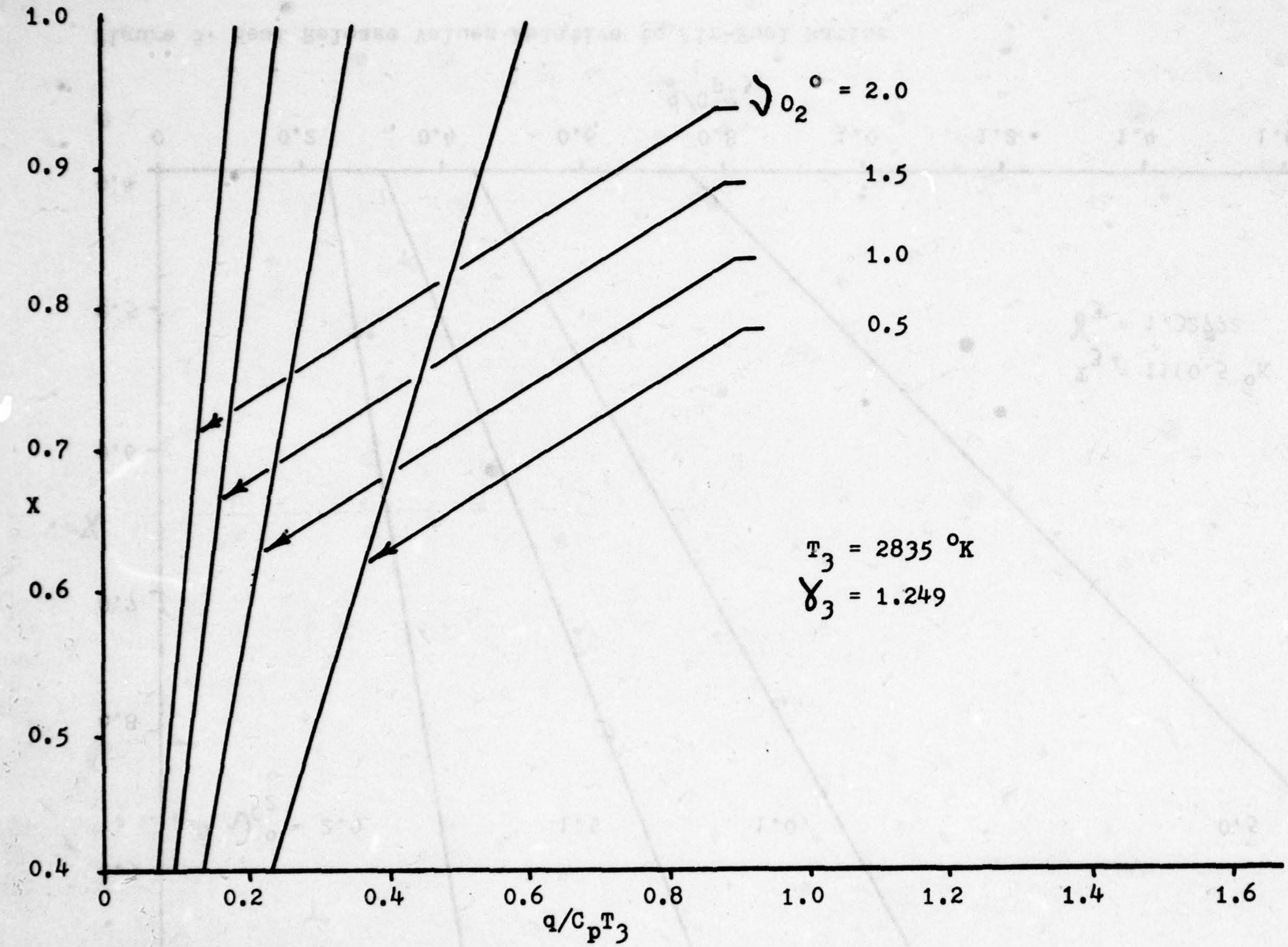


Figure 6. Heat Release Values Relative To Air-Fuel Ratios

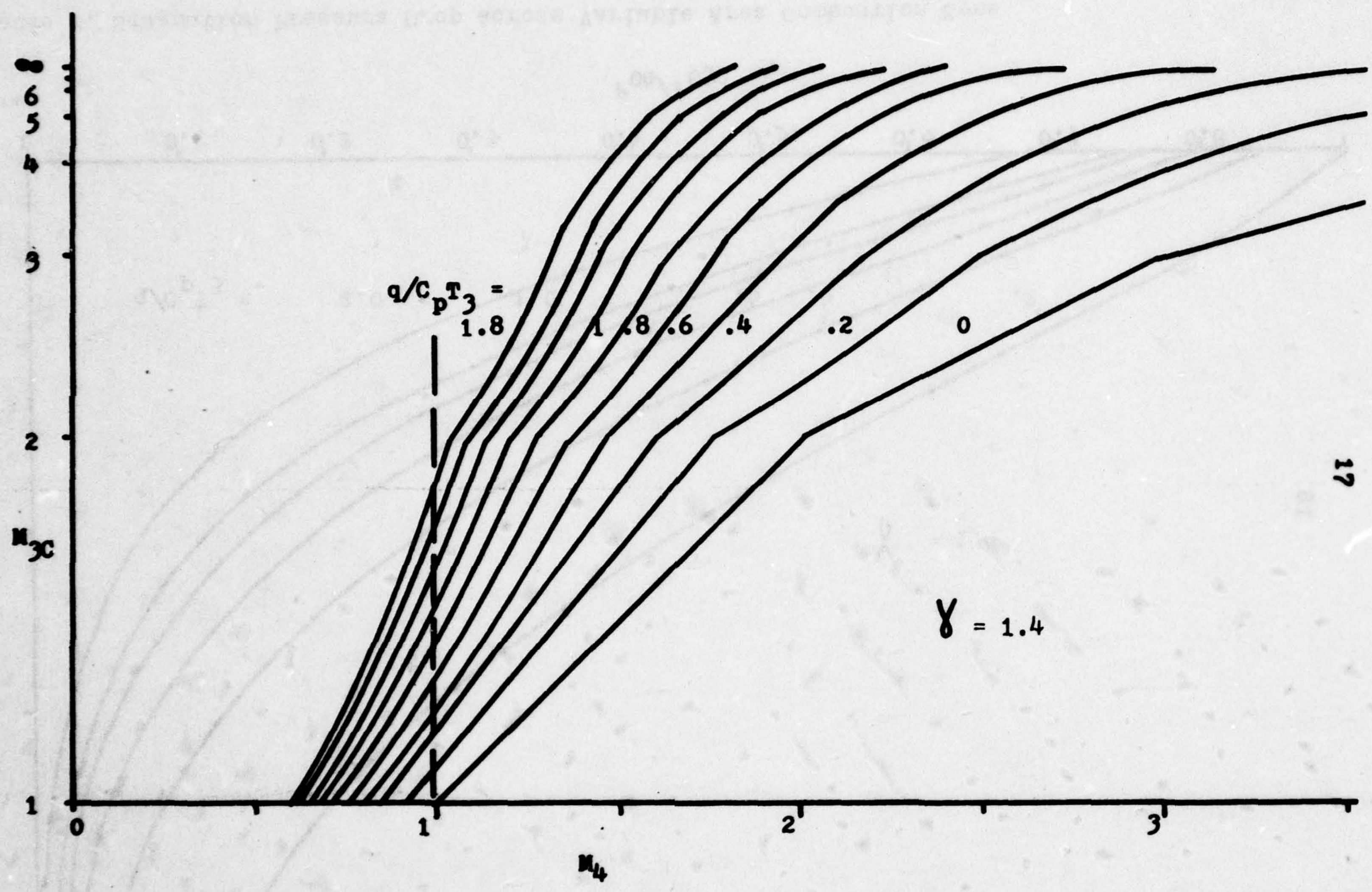


Figure 7. Supersonic Flow Required at Entrance to the Combustion Chamber as a Function of the Heat Release

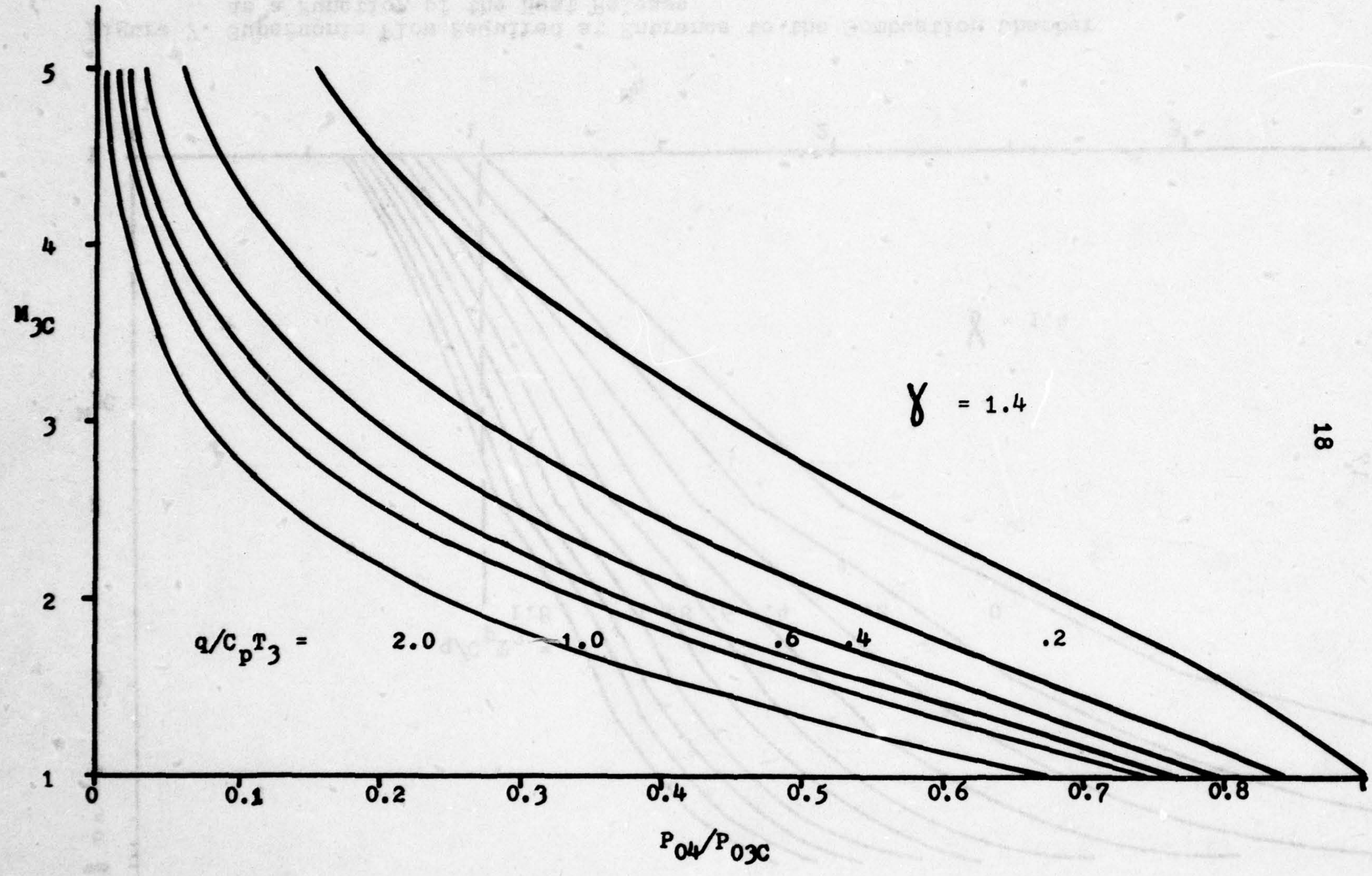


Figure 8. Stagnation Pressure Drop Across Variable Area Combustion Zone

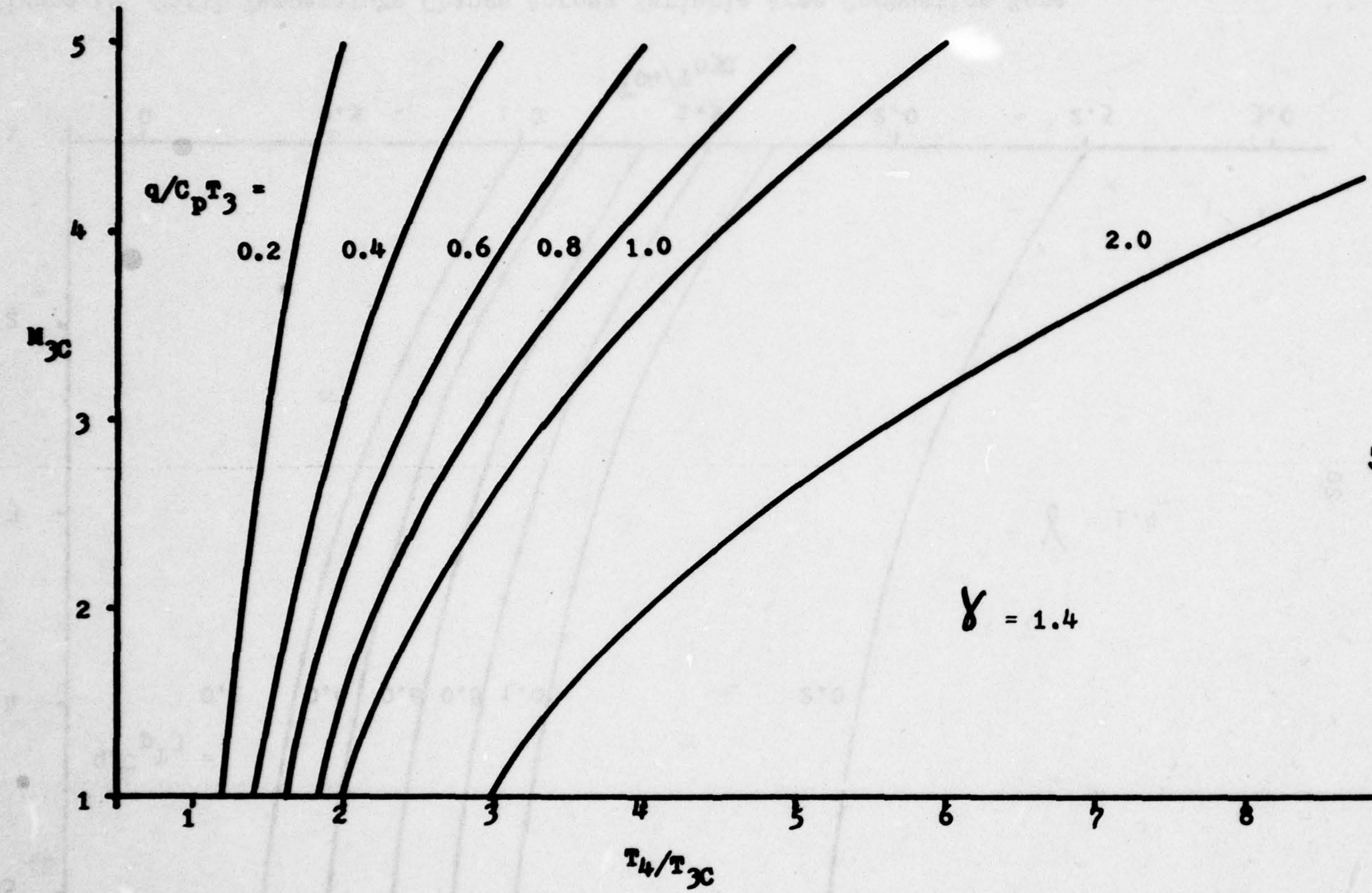


Figure 9. Temperature and Area Increase Across Variable Area Combustion Zone

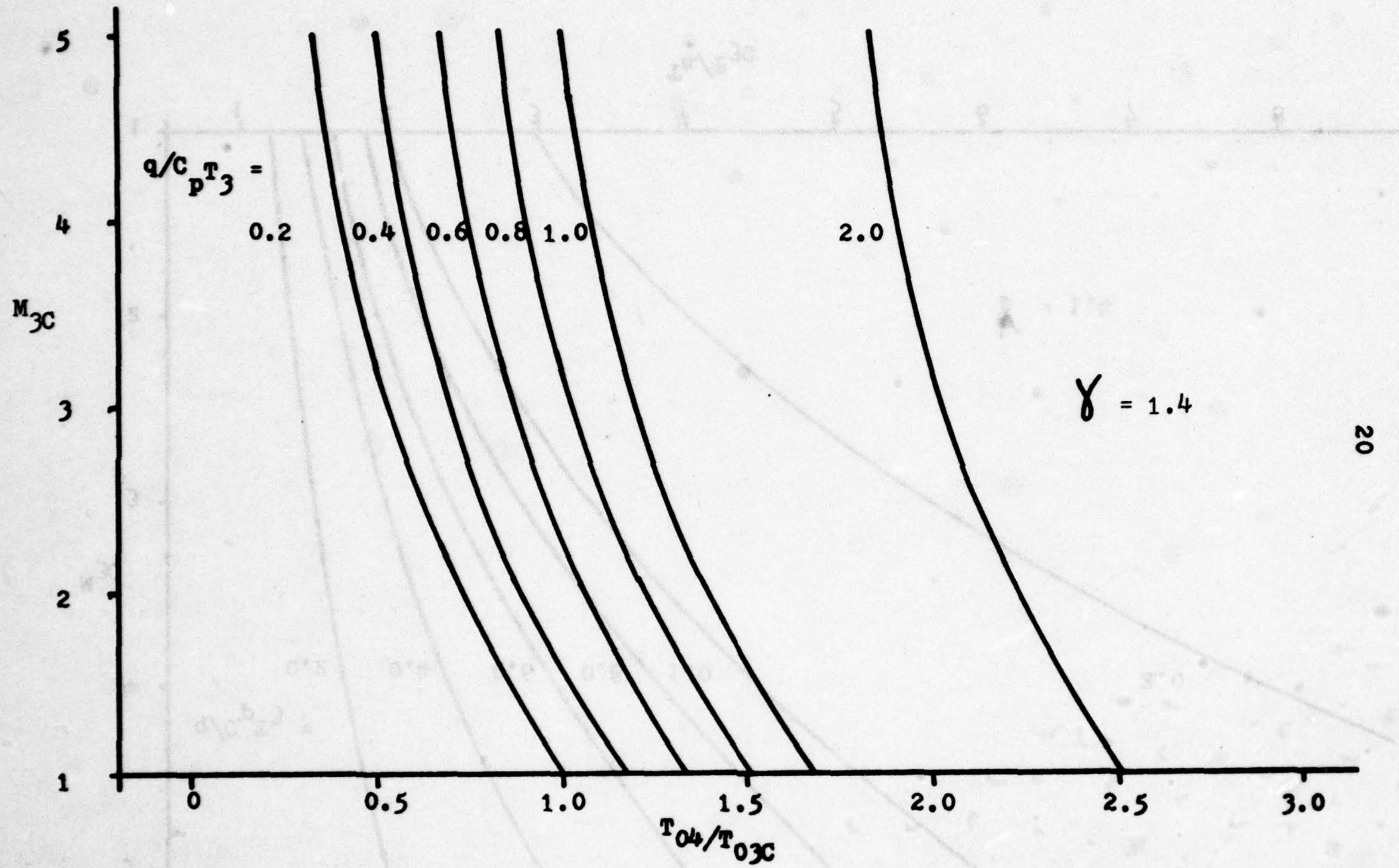


Figure 10. Total Temperature Change Across Variable Area Combustion Zone

with an appropriate increase in γ FROZ . Inspection of Figure 7 shows that for constant values of heat release coefficient at the combustion chamber exit, larger mach numbers are required at the diffuser exit to lower the resultant mach numbers at the combustion chamber exit.

SECTION VII

SUPERSONIC AIR FLOW AND HYDROGEN FUEL COMBUSTION CALCULATIONS

It was determined for the lower speeds of $M_\infty = 5$ and $\nu_{O_2}{}^{o} = 0.5$ that the temperature reduced to 739 °K for the shocked inlet and 754.9°K for the shock free inlet. For these calculations from then on out to the nozzle exit it was assumed that ignition of the hydrogen-air mixture was achieved by other means rather than self ignition as the flow would quench below approximately 900 °K. The next procedure is to calculate the fluid properties of the hydrogen-air mixture at the combustion entrance and exit for chemically reacting gases. Consider the energy equation,

$$h_{f\,abs}^{\,,3c} + \frac{u_{3c}^2}{2} = h_{f\,abs}^{\,,4} + \frac{u_4^2}{2}$$

The assumption of constant pressure combustion implies that dp=0 and therefore du=0 from the momentum equation.

$$\frac{\mathcal{R}T_{3c}}{m_{3c}} \sum_i n_{i,3c}\left[\frac{\Delta H_{f\,abs}}{\mathcal{R}T}\right]_i^{T_{3c}} = \frac{\mathcal{R}T_4}{m_4} \sum_i n_{i,4}\left[\frac{\Delta H_{f\,abs}}{\mathcal{R}T}\right]_i^{T_{4\,ext}}$$

That is, the enthalpy of the hydrogen-air mixture before combustion is equal to the enthalpy of the combustion of gases at the combustion chamber exit.

$$h_{f\,mix}^{T_{3c}} = X_{air}\, h_{f\,air}^{T_{air}} + X_{H_2}\, h_{f,H_2}^{T_{H_2}}$$

where X_{air} and X_{H_2} are the mass fractions of the air and hydrogen.

$$X_{air} = \frac{\nu_{O_2}^{\circ}\,(32 + 3.76(28.016))\ ^{Kg}/_{K\text{-}mole}}{\nu_{O_2}^{\circ}\,(32 + 3.76(28.016)) + 2.016\ ^{Kg}/_{K\text{-}mole}}$$

and

$$X_{hyd} = \frac{2.016\ ^{Kg}/K\text{-}mole}{\nu_{O_2}^{\circ}\,(32 + 3.76(28.016)) + 2.016\ ^{Kg}/_{K\text{-}mole}}$$

$$h_{f\,air} = \frac{R\,T_{3c}}{M_{3c}} \sum_i n_i \left(\frac{\Delta H_{f\,abs}}{R\,T}\right)_i^{T_{hyd}}\ ^{J}/_{Kg}$$

$$h_{f\,hyd} = \frac{R\,T_{hyd}}{M_{hyd}} \sum_i n_i \left(\frac{\Delta H_{f\,abs}}{R\,T}\right)_{H_2}^{T=1000\,^\circ K}\ ^{J}/_{Kg}$$

or

$$h_{f\,hyd} = \frac{8314.33\,(1000)}{2.016} \left(\frac{\Delta H_{f\,abs}}{R\,T}\right)_{H_2}^{T=1000\,^\circ K}\ ^{J}/_{Kg}$$

Recalling that it is assumed that the temperature of the hydrogen entering the airstream is 1000 $^\circ$K or less (equivalent to the temperature of the airstream.) For example, if the airstream was 3000 $^\circ$K, the hydrogen temperature is 1000 $^\circ$K, and if the temperature of the airstream were 950 $^\circ$K, the hydrogen temperature is given as 950 $^\circ$K also. The reason for this was to avoid the possibility of dissociation

of the H_2 molecules into H atoms before they enter the airstream. This would affect the enthalpy, molecular weight of the mixture. Even though this effect would be slight the enthalpic state of hydrogen is much larger than air because of its much smaller molecular weight of 2.016 versus 28.853 for air. This could mean changes of up to 100 ^{o}K in the final computations, and it is also unlikely that H_2 would be injected into the airstream at higher temperatures.

Now to determine the temperature at the exit of the combustion chamber, values are actually just guessed at approximately 1500-2000 ^{o}K above that of the air at the entrance of the combustion chamber. The pressure of course was assumed to be constant.

The first thing to do is to calculate the mole fractions at a given pressure and temperature.

$$n_O = K^{(\frac{1}{2} O_2)} \sqrt{n_{O_2}}$$

$$n_{H_2} = \left\{ \sqrt{\left(\frac{A}{B}\right)^2 + \frac{1 - 0.5\, n_O}{B}} - \frac{A}{B} \right\}^2$$

where

$$A = 0.25 \left[K^{(\frac{1}{2} H_2)} + \left(\frac{n_{O_2}^{g} + n_{N_2}^{g}}{n_{H_2}^{g}} + 1 \right) \left(K^{(\frac{1}{2} H_2)} + K^{(OH)} \sqrt{n_{O_2}} \right) \right]$$

and

$$B = 0.5 + \left(\frac{n_{O_2}^{g} + n_{N_2}^{g}}{n_{H_2}^{g}} + 0.5 \right) \left(1 + K^{(H_2O)} \sqrt{n_{O_2}} \right)$$

$$n_H = K^{(\frac{1}{2} H_2)} \sqrt{n_{H_2}}$$

$$n_{OH} = K^{(OH)} \sqrt{n_{O_2}} \sqrt{n_{H_2}}$$

$$n_{H_2O} = K^{(H_2O)} \sqrt{n_{O_2}}\; n_{H_2}$$

$$n_{N_2} = \left\{ \sqrt{\left[0.25 K^{(NO)} \sqrt{n_{O_2}}\right]^2 + \left(n_{H_2O} + n_{H_2} + 0.5\left[n_{OH} + n_H\right]\right) \frac{n^g_{N_2}}{n^g_{H_2}}} - 0.25 K^{(NO)} \sqrt{n_{O_2}} \right\}^2$$

and

$$n_{NO} = K^{(NO)} \sqrt{n_{O_2}} \sqrt{n_{N_2}}$$

These calculations are repeated with improved values of the estimated mole fractions of oxygen until

$$\left| \frac{n^g_{O_2}}{n^g_{H_2}} - \nu^{\circ}_{O_2} \right| < .001 \qquad \frac{n^g_{O_2}}{n^g_{H_2}} = \frac{n_{O_2} + 0.5(n_O + n_{H_2O} + n_{OH} + n_{NO})}{n_{H_2O} + n_{H_2} + 0.5(n_{OH} + n_H)}$$

Successively closer values of the enthalpic state at the exit of the combustion are determined until an accuracy of

$$\left| \frac{h_{f\,mix}^{,T_4} - h_{f\,mix}^{,T_{3C}}}{h_{f\,mix}^{,T_4}} \right| \leq 0.01$$ **is achieved.**

Since again the mach number can be calculated in the same manner as at the nozzle throat. Viewing the results of the calculations, it is evident that water and nitrogen are the final chemical constituients provided the temperatures are not to great and the hydrogen, oxygen and nitrogen atoms are not allowed to reform into molecules.

SECTION VIII

ISENTROPIC FLOW CALCULATIONS AT NOZZLE

The most desirable or ideal state at the exit of the engine would be that no underexpanded flow, $P_{exit} < P_1$ or overexpanded flow where $P_{exit} > P_1$ would exit the end of the nozzle. For the purpose of calculating the ideal nozzle flow the pressure was assumed equal to that entering the engine behind the bow shock wave. $P_5 = 0.02$ for $M_1 = 5$ and $P_5 = 0.04$ for $M_1 = 8$. Also it was assumed that the flow went from the combustion chamber exit to the nozzle exit isentropically. A reasonably valid assumption provided the hydrogen gas combustion reaction is complete. That is, the hydrogen gas has released all its heat content within the combustion chamber and no additional heat is released within the nozzle exit. The decrease in temperature and resulting increase in velocity of the gases is a transformation of molecular random motion into more ordered and directional motion.

The entropy at the exit of the combustion chamber can be determined as the temperature, pressure and mole fractions are known.

$$\left(\frac{S}{R_2}\right)^{T_4} = \frac{m_2}{m_4}\left[\sum_i n_{i,4}\left(\frac{S}{R}\right)_i^{P=1\,T_4} - \sum_i n_{i,4} - \ln P_4\right]$$

Pressure and temperature will decrese for nozzle expansion and the velocity will increase. The frozen flow mach number and γ are calculated at station 4 and using these values the estimates at station 5 are made with perfect gas isentropic relationships.

$$\left.\frac{P_5}{P_{05}}\right]_{M_5} = \frac{P_5}{P_4}\left.\frac{P_4}{P_{04}}\right]_{M_4}$$

where

$$\frac{P_{04}}{P_4} = \left[1 + \frac{\gamma-1}{2} M_4^2\right]^{\gamma/\gamma-1}$$

Also

$$M_5 = \left\{\left(\left(\frac{P_{05}}{P_5}\right)^{\gamma-1/\gamma} - 1\right)\frac{2}{\gamma-1}\right\}^{1/2}$$

After estimating M_5 the temperature corresponding to the pressure is determined.

$$T_5 = \frac{T_5}{T_{05}}\frac{T_{04}}{T_4}T_4 = \frac{\left[1 + \frac{\gamma-1}{2} M_4^2\right]}{\left[1 + \frac{\gamma-1}{2} M_5^2\right]} T_4$$

Keeping in mind that the value of γ used is that frozen from the combustion chamber exit. The temperature and pressure are adjusted accounting for chemical reactions and with this estimate of temperature the mole fractions from the previous equations given are calculated. The entropy is,

$$\left(\frac{S}{R_2}\right)^{T_5} = \frac{m_2}{m_4}\left[\sum_i n_{i,4}\left(\frac{S}{R}\right)_i^{T_5} - \sum_i n_{i,5}\ln n_{i,5} - \ln P_5\right]$$

The temperature T_5 is adjusted until the entropy at station 5 is within 0.01% of that at station 4. The corresponding absolute enthalpy is then determined.

$$\left.\frac{h_{f_{abs}}}{R_2 T_2}\right)^{T_5} = \frac{\mathcal{M}_2}{\mathcal{M}_5}\frac{T_5}{T_2}\sum_i n_{i,5}\left(\frac{\Delta H_{f_{abs}}}{\mathcal{R}T}\right)^{T_5}$$

$$u_5^{CALC} = \left\{\left[\left(\frac{h_{f_{abs}}}{R_2 T_2}\right)^{T_4} - \left(\frac{h_{f_{abs}}}{R_2 T_2}\right)^{T_5}\right]\frac{2(8314.33)\,T_4}{\mathcal{M}_4} + u_4\right\}^{1/2}$$

$$\gamma_5^{FROZ} = \frac{\sum_i n_{i,5}\left(\frac{C_p}{\mathcal{R}}\right)^{T_5}}{\sum_i n_{i,5}\left(\frac{C_p}{\mathcal{R}}\right)^{T_5} - 1}$$

$$M_5^{FROZ} = \frac{u_5^{CALC}}{\sqrt{\gamma_5^{FROZ}\,\frac{\mathcal{R}}{\mathcal{M}_5}\,T_5}}$$

SECTION IX

CALCULATION OF AREA RATIOS FROM COMPUTED FLOW PROPERTIES

The area ratios can now be determined from the conservation of mass and the equation of state.

$$(\rho u A)_1 = (\rho u A)_2 \qquad \rho = \frac{P}{T}\frac{\mathcal{M}}{\mathcal{R}}$$

or $$\frac{A_2}{A_1} = \frac{T_2}{T_1}\frac{P_1}{P_2}\frac{\mathcal{M}_1}{\mathcal{M}_2}\frac{u_1}{u_2}$$

Note that a specific area cannot be found for any one location. A reference area must be established. The sonic throat is chosen as the reference area as it supposedly represents the smallest area. The area ratio at the throat is given and is that location where the flow is sonic (M = 1).

SECTION X

SPECIFIC NET THRUST AND TSFC

The specific net thrust (SNT) and thrust specific fuel consumption (TSFC) are determined as follows:

$$\frac{T}{\dot{m}_a} = (1 + f)u_5 - u_1 \qquad P_a = P_e$$

$\dot{m}_a$ - mass flow rate of air through the engine configuration

f - fuel air ratio

u_5 - exit velocity of burned gases

u_1 - flight velocity of the engine (initially specified)

$$f = \frac{\text{mass fuel / per unit time}}{\text{mass air / per unit time}} = \frac{2.016 \ \text{Kg/K-mole - unit time}}{\nu_{O_2}^{\circ}\left(32 + (3.76)(28.016)\right)\frac{\text{Kg}}{\text{K-mole-unit time}}}$$

$$f = \frac{2.016}{0.5(32 + 3.76(28.016))} = 0.0293578 \quad \text{for } \nu_{O_2}^{\circ} = 1/2$$

$$f = \frac{2.016}{2(32 + 3.76(28.016))} = 0.0073394 \quad \text{for } \nu_{O_2}^{\circ} = 2$$

$$TSFC = \frac{\dot{m}_f}{T} = f \Big/ \frac{T}{\dot{m}_a}$$

SECTION XI

CONCLUDING COMMENTS

The resulting specific net thrusts and associated TSFC are rather high. As would be expected the greatest amount of thrust would be provided for the richest mixture of hydrogen to air at $\nu_{O_2}^{\circ} = 0.5$. The thrust falls off dramatically for leaner mixtures and for the shocked inlet at $M_\infty = 10$ for $\nu_{O_2}^{\circ} = 2$ negative thrust or drag is provided.

Rather encouraging results are obtained for the shocked inlet. The thrust values are reasonably high and the associated TSFC's are almost double that of some typical ramjets (designed and in operation.) This type of design would require that the stagnation pressure drop such that P_{3C}/P_{03C}, P_4/P_{04}, and P_5/P_{05} be below values of 0.528 or it would not be possible to obtain supersonic flow in the aft side of the diffuser. This can be determined from perfect gas tables, shock tables, and the graphs included herein for stagnation pressure drops across the combustion chamber.

For $M_\infty = 5$, $\nu_{O_2}^{\circ} = 0.5$, and the shocked inlet,

$P_{3C}/P_{03C} = 0.1113$ $\quad$ $P_4/P_{04} = 0.3969$ $\quad$ $P_5/P_{05} = 0.10994$

all of which are below $P/P_0 = 0.528$. This means the flow will indeed go supersonic. Similarly, the other conditions can be checked.

TABLE 1 CALCULATED SNT AND TSFC VALUES

SHOCKED INLET ENGINE

M_∞	$\nu_{O_2}^{o}$	$\mathcal{T}/m_a$ (N/Kg/sec)	TSFC (Kg/hr/N)
5	0.5	341.334	0.3096
5	2	110.312	0.2395
10	0.5	441.404	0.2394
10	2	-359.567	NA

SHOCK FREE ENGINE

M_∞	$\nu_{O_2}^{o}$	$\mathcal{T}/m_a$ (N/Kg/sec	TSFC (Kg/hr/N)
5	0.5	901.037	0.1173
5	2	230.790	0.1145
10	0.5	739.172	0.1430
10	2	-12.412	NA

SOME TYPICAL VALUES OF TSFC FOR OTHER TYPES OF ENGINES ARE

RAMJET	0.173 - 0.265	(N/Kg/sec)	M = 2
TURBOJETS	0.0763 - 0.1078	(N/Kg/sec)	STATIC
TURBOFANS	0.0509 - 0.0611	(N/Kg/sec)	STATIC

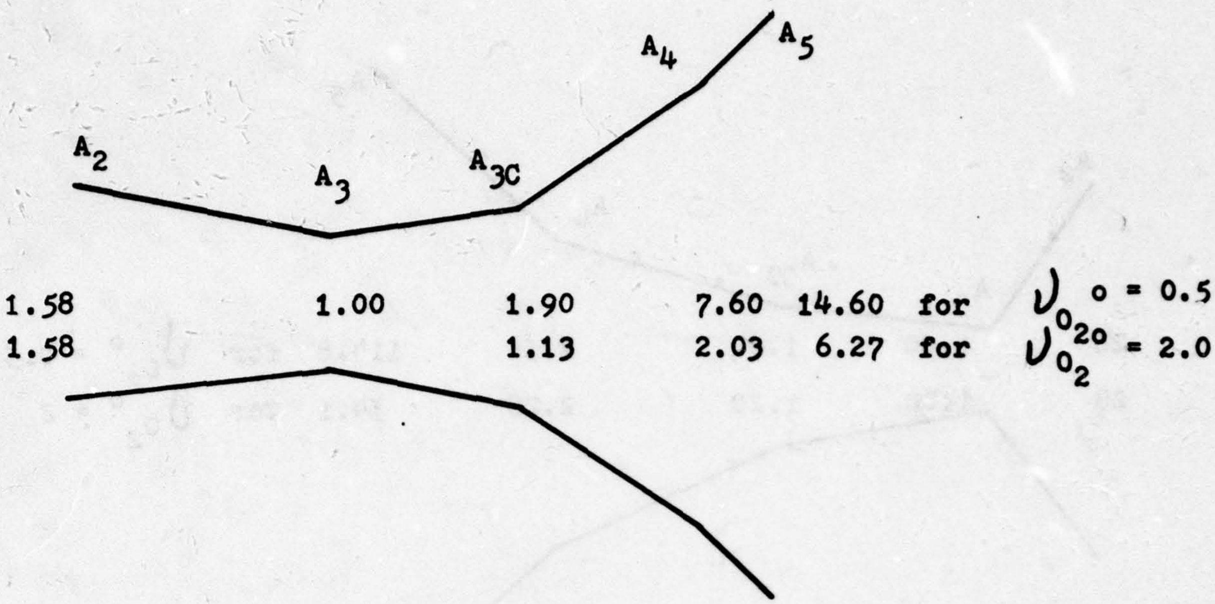


Figure 11. Shocked Inlet for $M_\infty = 5$, $\nu_{o_2}{}^{o}$ 0.5, 2.0 with Area Relationships

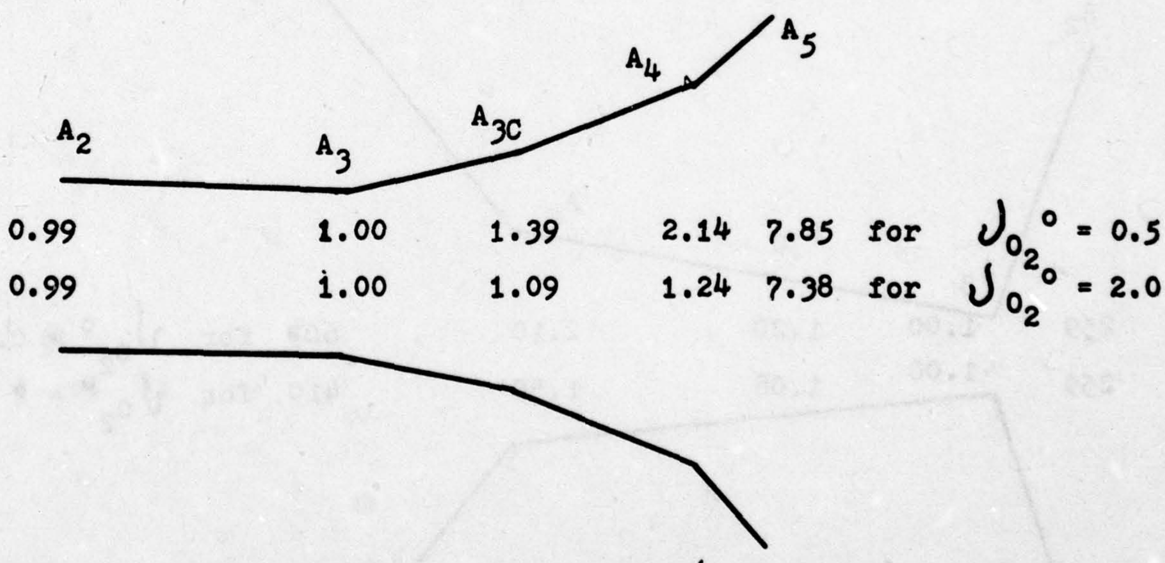


Figure 12. Shocked Inlet for $M_\infty = 10$, $\nu_{o_2}{}^{o} = 0.5, 2.0$ with Area Relationships

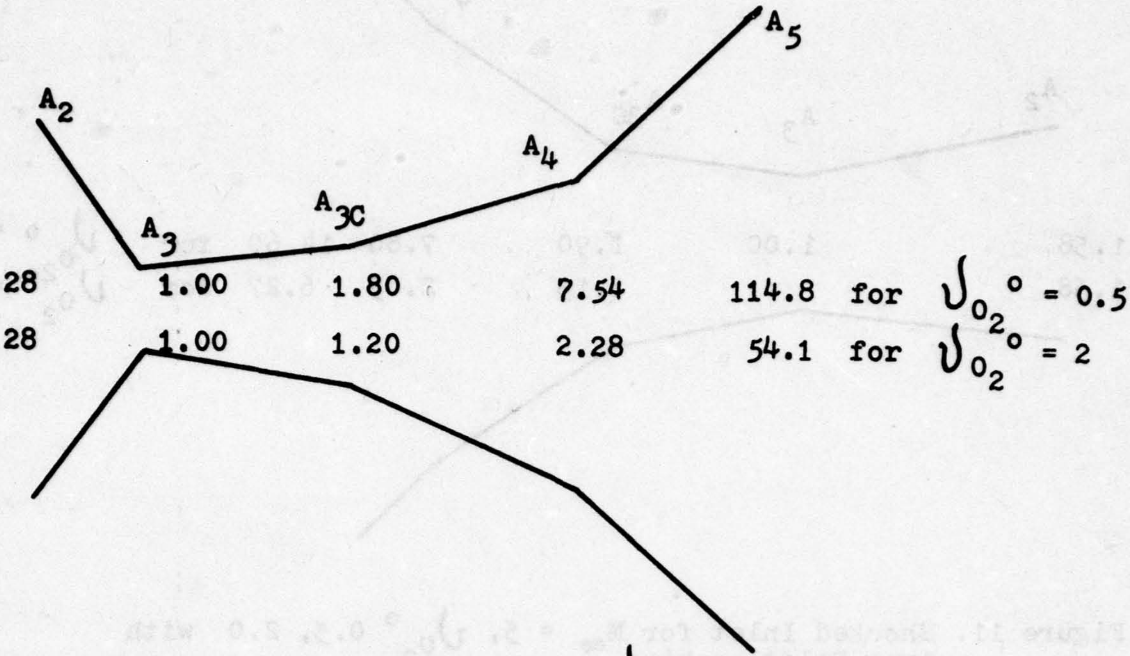


Figure 13. Shock Expelled for M_∞ = 5, $\nu_{O_2}{}^{o}$ = 0.5, 2 with Area Relationships

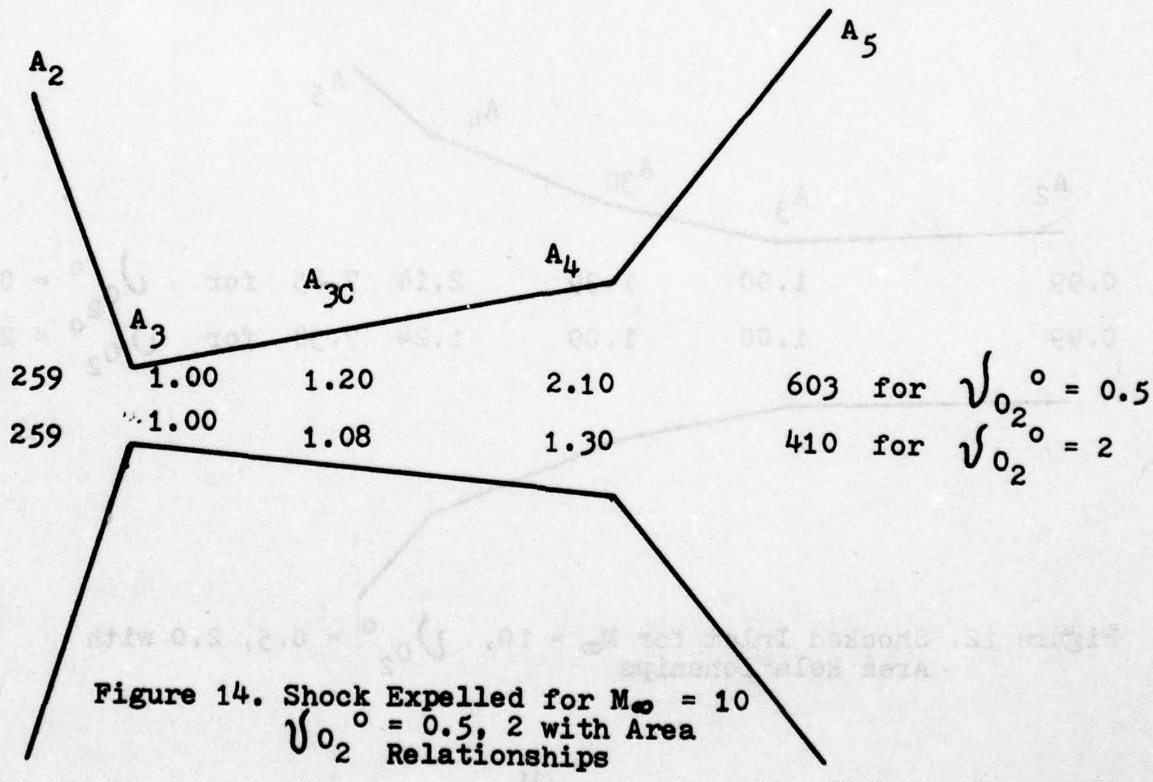


Figure 14. Shock Expelled for M_∞ = 10 $\nu_{O_2}{}^{o}$ = 0.5, 2 with Area Relationships

While the values of thrust and TSFC for the shock free engine look to be promising, it must also be considered that the static pressures of up to 272 atmospheres would be prohibitive. In fact, it would be necessary to open up the diffuser rather than closing it to provide permissible operating pressures. Also, to prevent choking in the combustion chamber the engine would have to be opened even more. This would require a tremendously large engine with a large associated wave drag. As such, only the shocked inlet configuration appears to be promising.

A method of injecting and combusting the gases across oblique shock waves in the combustion chamber for the shocked inlet configuration should be investigated as to its feasibility. Also, the same methods outlined in this paper could be used to investigate the feasibility of an external ramp over which combustion would take place on the aft side.

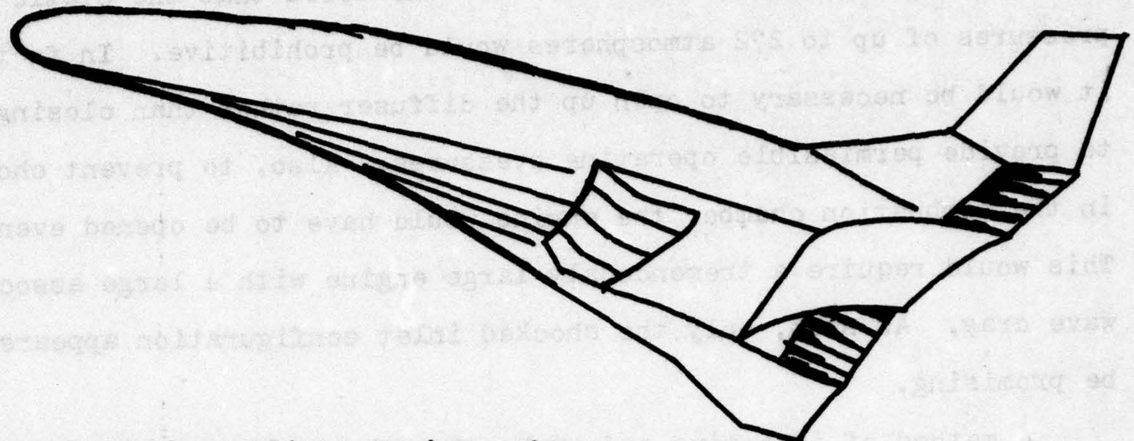


Figure 15. Typical Flight Vehicle with Supersonic Ramjet Engine

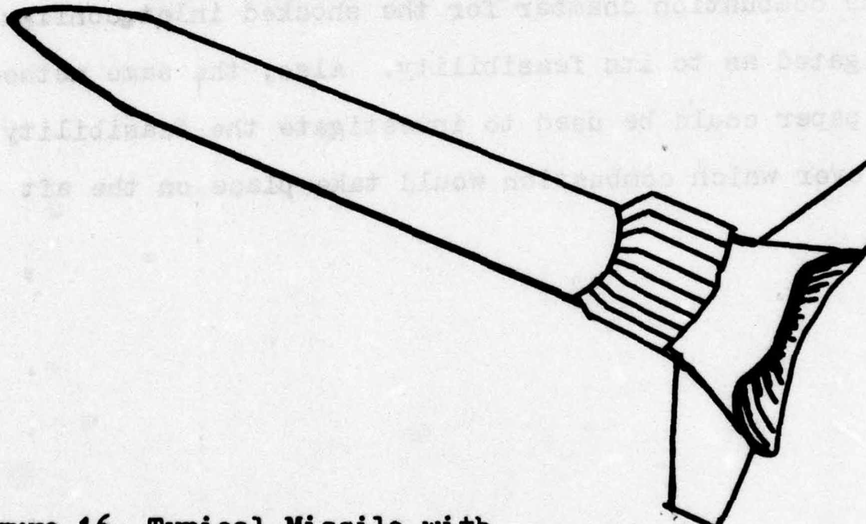


Figure 16. Typical Missile with Supersonic Ramjet Engine

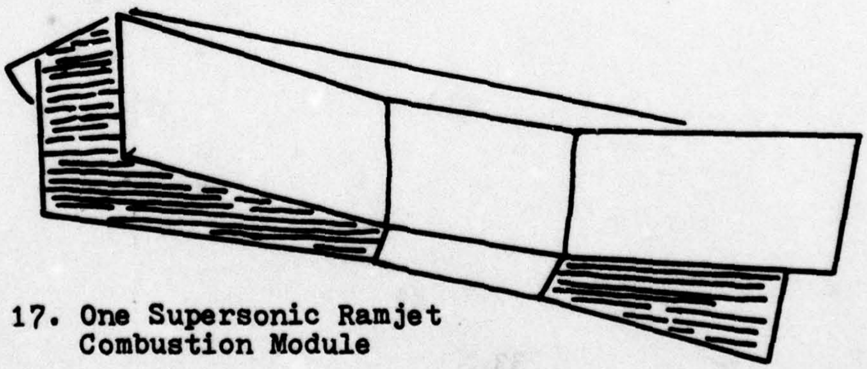


Figure 17. One Supersonic Ramjet Combustion Module

TABLE 2 COEFFICIENTS $a^{(j)}(T)$ OF EQUILIBRIUM CONSTANTS $K_p^{(j)}(T)$

T (K)	[illegible] $a^{(H)}$	[illegible] $a^{(O)}$	[illegible] $a^{(OH)}$	[illegible] $a^{(H_2O)}$
1100	14.038	39.[illegible]	6.4760	0.114[illegible]
1200	14.342	39.7[illegible]	6.3[illegible]	0.10931
1300	14.619	40.[illegible]	6.3[illegible]	0.10[illegible]
1400	14.853	40.101	6.29[illegible]	0.1011[illegible]
1500	15.049	40.[illegible]	6.2436	0.0[illegible]
1600	15.252	41.0[illegible]3	6.1913	0.09[illegible]
1700	15.428	41.244	6.1493	0.09[illegible]
1800	15.602	41.3[illegible]	6.1027	0.0[illegible]12
1900	15.757	41.438	6.0564	0.09[illegible]
2000	15.893	41.480	6.0105	0.0[illegible]
2100	16.002	41.492	5.9772	0.08811
2200	16.119	41.475	5.9440	0.08718
2300	16.211	41.434	5.9110	0.08644
2400	16.275	41.364	5.8783	0.08582
2500	16.351	41.269	5.8457	0.08531
2600	16.405	41.207	5.8133	0.08483
2700	16.451	41.112	5.7810	0.08440
2800	16.495	40.993	5.7490	0.08403
2900	16.543	40.862	5.7171	0.08370
3000	16.585	40.719	5.6854	0.08352
3100	16.602	40.553	5.6594	0.08328
3200	16.620	40.391	5.6334	0.08307
3300	16.635	40.225	5.6076	0.08295
3400	16.642	40.061	5.5820	0.08283
3500	16.645	39.901	5.5564	0.08284
3600	16.645	39.738	5.5310	0.08282
3700	16.638	39.575	5.5056	0.08283
3800	16.625	39.413	5.4804	0.08286
3900	16.612	39.256	5.4553	0.08292
4000	16.602	39.087	5.4303	0.08300
4100	16.588	38.904	5.4081	0.08303
4200	16.573	38.726	5.3860	0.08307
4300	16.557	38.544	5.3639	0.08313
4400	16.539	38.363	5.3420	0.08322
4500	16.504	38.225	5.3201	0.08331
4600	16.479	38.046	5.2984	0.08342
4700	16.453	37.868	5.2767	0.08352
4800	16.423	37.690	5.2551	0.08359
4900	16.392	37.517	5.2336	0.08366
5000	16.359	37.338	5.2122	0.08374
5100	16.325	37.159	5.1909	0.08383
5200	16.289	36.985	5.1696	0.08392
5300	16.240	36.811	5.1485	0.08403
5400	16.206	36.635	5.1274	0.08414
5500	16.163	36.463	5.1064	0.08426
5600	16.122	36.292	5.0855	0.08436
5700	16.079	36.118	5.0647	0.08447
5800	16.035	35.949	5.0440	0.08458
5900	15.991	35.780	5.0234	0.08471
6000	15.943	35.613	5.0028	0.08490
$\frac{\Delta E_0^{(j)}}{R}$	25942	89615	4675	-20736
$b^{(j)}$	0.5	0.5	0.0	-0.5

$$K_p^{(j)}(T) = a^{(j)}(T_1)\left[\frac{a^{(j)}(T_1+100)}{a^{(j)}(T_1)}\right]^{\left(\frac{T-T_1}{100}\right)} \cdot T^{b^{(j)}} \cdot \exp\left[-(\Delta E_0^{(j)}/R)\cdot(1/T)\right]\left[\text{atm}^{b^{(j)}}\right]$$

$$T_1 < T < T_1 + 100$$

TABLE 3 COEFFICIENTS $a^{(j)}(T_1)$ OF EQUILIBRIUM CONSTANTS $K_p^{(j)}(T_1)$

T_1 (K)	$\frac{1}{2}N_2 = N$ $a^{(N)}$	$\frac{1}{2}N_2 + \frac{1}{2}O_2 = NO$ $a^{(NO)}$	$CO + \frac{1}{2}O_2 = CO_2$ $a^{(CO_2)}$
1100	36.800	4.2716	1.7175 -5
1200	37.353	4.2982	1.6580 -5
1300	37.909	4.3215	1.6124 -5
1400	38.272	4.3432	1.5757 -5
1500	38.555	4.3623	1.5537 -5
1600	38.873	4.3793	1.5341 -5
1700	39.122	4.3939	1.5241 -5
1800	39.322	4.4079	1.5127 -5
1900	39.444	4.4194	1.5048 -5
2000	39.523	4.4256	1.4985 -5
2100	39.674	4.4393	1.4977 -5
2200	39.765	4.4460	1.4988 -5
2300	39.813	4.4531	1.4987 -5
2400	39.845	4.4576	1.5002 -5
2500	39.865	4.4620	1.5050 -5
2600	39.865	4.4651	1.5137 -5
2700	39.861	4.4669	1.5199 -5
2800	39.845	4.4687	1.5236 -5
2900	39.809	4.4695	1.5300 -5
3000	39.734	4.4705	1.5366 -5
3100	39.701	4.4709	1.5441 -5
3200	39.666	4.4705	1.5526 -5
3300	39.630	4.4695	1.5615 -5
3400	39.586	4.4687	1.5703 -5
3500	39.539	4.4669	1.5786 -5
3600	39.488	4.4647	1.5870 -5
3700	39.428	4.4620	1.5956 -5
3800	39.369	4.4584	1.6040 -5
3900	39.302	4.4549	1.6128 -5
4000	39.220	4.4513	1.6214 -5
4100	39.157	4.4509	1.6297 -5
4200	39.083	4.4380	1.6383 -5
4300	39.013	4.4322	1.6470 -5
4400	38.950	4.4256	1.6570 -5
4500	38.888	4.4194	1.6659 -5
4600	38.830	4.4132	1.6746 -5
4700	38.775	4.4070	1.6835 -5
4800	38.721	4.4009	1.6922 -5
4900	38.675	4.3943	1.7014 -5
5000	38.628	4.3877	1.7101 -5
5100	38.582	4.3815	1.7191 -5
5200	38.536	4.3750	1.7280 -5
5300	38.501	4.3684	1.7372 -5
5400	38.463	4.3614	1.7461 -5
5500	38.428	4.3540	1.7552 -5
5600	38.401	4.3475	1.7640 -5
5700	38.374	4.3405	1.7720 -5
5800	38.351	4.3335	1.7810 -5
5900	38.332	4.3267	1.7900 -5
6000	38.317	4.3198	1.7985 -5
$\left(\frac{\Delta E_0}{R}\right)^{(j)}$	56613	10799	-33598
$\nu^{(j)}$	0.5	0.0	0.125

$$K^{(j)}(T) = a^{(j)}(T_1)\left[\frac{a^{(j)}(T_1+100)}{a^{(j)}(T_1)}\right]^{\left(\frac{T-T_1}{100}\right)} \cdot T^{\nu^{(j)}} \cdot \exp\left[-(\Delta E_0/R)^{(j)} \cdot (1/T)\right]\left[\text{atm}^{\Delta\nu^{(j)}}\right]$$

$$T_1 < T < T_1 + 100$$

TABLE 4 EQUILIBRIUM CONSTANTS, $K^{(j)}{}_{atm}{}^{\Delta\nu(j)}$

T (K)	$K_p^{(\frac{1}{2}H_2)}$ $atm^{\frac{1}{2}}$ $\frac{1}{2}H_2 = H$	$K_p^{(\frac{1}{2}O_2)}$ $atm^{\frac{1}{2}}$ $\frac{1}{2}O_2 = O$	$K^{(OH)}$ atm^{0} $\frac{1}{2}H_2 + \frac{1}{2}O_2 \rightleftharpoons OH$	$K_p^{(H_2O)}$ $atm^{-\frac{1}{2}}$ $H_2 + \frac{1}{2}O_2 = H_2O$
1100	2.5704 -8	2.4774 -9	9.1833 -2	7.6384 8
1200	1.9634 -7	2.4889 -8	1.2972 -1	7.9250 7
1300	1.1015 -6	1.7579 -7	1.7378 -1	1.1580 7
1400	4.8417 -6	9.3972 -7	2.2284 -1	2.2233 6
1500	1.7498 -5	4.0272 -6	2.7606 -1	5.3088 5
1600	5.4075 -5	1.4388 -5	3.3343 -1	1.5130 5
1700	1.4655 -4	4.4361 -5	3.9264 -1	5.0003 4
1800	3.5645 -4	1.2078 -4	4.5394 -1	1.8821 4
1900	7.9068 -4	2.9580 -4	5.1761 -1	7.6913 3
2000	1.6181 -3	6.6374 -4	5.8076 -1	3.4674 3
2100	3.1046 -3	1.3804 -3	6.4565 -1	1.6808 3
2200	5.6105 -3	2.6853 -3	7.0958 -1	8.7498 2
2300	9.6383 -3	4.9317 -3	7.7446 -1	4.8084 2
2400	1.5849 -2	8.6099 -3	8.3753 -1	2.7733 2
2500	2.5061 -2	1.4388 -2	8.9950 -1	1.6749 2
2600	3.8194 -2	2.3121 -2	9.6161 -1	1.0495 2
2700	5.6624 -2	3.5810 -2	1.0233 0	6.8077 1
2800	8.1470 -2	5.3951 -2	1.0814 0	4.5499 1
2900	1.1455 -1	7.8886 -2	1.1402 0	3.1261 1
3000	1.5740 -1	1.1246 -1	1.1967 0	2.2029 1
3100	2.1184 -1	1.5668 -1	1.2531 0	1.5885 1
3200	2.7990 -1	2.1380 -1	1.3062 0	1.1666 1
3300	3.6392 -1	2.8642 -1	1.3583 0	8.7498 0
3400	4.6559 -1	3.7757 -1	1.4125 0	6.6681 0
3500	5.8749 -1	4.8978 -1	1.4622 0	5.1523 0
3600	7.3282 -1	6.2517 -1	1.5101 0	4.0458 0
3700	9.0365 -1	7.8886 -1	1.5560 0	3.2137 0
3800	1.0990 0	9.8401 -1	1.6032 0	2.5882 0
3900	1.3274 0	1.2134 0	1.6444 0	2.1038 0
4000	1.5849 0	1.4791 0	1.6866 0	1.7298 0
4100	1.8793 0	1.7865 0	1.7298 0	1.4355 0
4200	2.2080 0	2.1380 0	1.7701 0	1.1995 0
4300	2.5823 0	2.5351 0	1.8072 0	1.0116 0
4400	2.9923 0	2.9854 0	1.8450 0	8.6099 -1
4500	3.4435 0	3.4914 0	1.8836 0	7.3621 -1
4600	3.9355 0	4.0551 0	1.9143 0	6.3533 -1
4700	4.4771 0	4.6881 0	1.9498 0	5.5081 -1
4800	5.0699 0	5.3703 0	1.9815 0	4.7973 -1
4900	5.7148 0	6.1376 0	2.0137 0	4.2073 -1
5000	6.3973 0	6.9663 0	2.0464 0	3.7154 -1
5100	7.1450 0	7.8524 0	2.0749 0	3.2885 -1
5200	7.9433 0	8.8308 0	2.1038 0	2.9242 -1
5300	8.7902 0	9.8855 0	2.1281 0	2.6122 -1
5400	9.6828 0	1.1015 1	2.1528 0	2.3442 -1
5500	1.0641 1	1.2246 1	2.1827 0	2.1135 -1
5600	1.1641 1	1.3552 1	2.2029 0	1.9099 -1
5700	1.2706 1	1.4928 1	2.2284 0	1.7296 -1
5800	1.3836 1	1.6406 1	2.2491 0	1.5740 -1
5900	1.5031 1	1.7947 1	2.2751 0	1.4388 -1
6000	1.6255 1	1.9584 1	2.2961 0	1.3183 -1

TABLE 5 EQUILIBRIUM CONSTANTS, $K_p^{(j)}$ atm (j)

T (K)	$K_p^{(\frac{1}{2}N_2)}$ atm$^{\frac{1}{2}}$ $\frac{1}{2}N_2 = N$	$K^{(NO)}$ atm^0 $\frac{1}{2}N_2 + \frac{1}{2}O_2 = NO$	$K_p^{(CO_2)}$ atm$^{-\frac{1}{2}}$ $CO + \frac{1}{2}O_2 = CO_2$
1100	5.4325 -20	2.3281 -4	7.5858 8
1200	4.1976 -18	5.3088 -4	5.8076 7
1300	1.6672 -16	1.0666 -3	6.6222 6
1400	3.9264 -15	1.9409 -3	1.0328 6
1500	6.0674 -14	3.2584 -3	2.0701 5
1600	6.6834 -13	5.1286 -3	5.0816 4
1700	5.5463 -12	7.6560 -3	1.4791 4
1800	3.6559 -11	1.0914 -2	4.9317 3
1900	1.9724 -10	1.5031 -2	1.8493 3
2000	8.9950 -10	1.9999 -2	7.6560 2
2100	3.5563 -9	2.5942 -2	3.4594 2
2200	1.2445 -8	3.2810 -2	1.6827 2
2300	3.8994 -8	4.0644 -2	8.7096 1
2400	1.1117 -7	4.9545 -2	4.7753 1
2500	2.9174 -7	5.9293 -2	2.7542 1
2600	7.0958 -7	7.0246 -2	1.6558 1
2700	1.6218 -6	8.1846 -2	1.0351 1
2800	3.4914 -6	9.4406 -2	6.6834 0
2900	7.1285 -6	1.0789 -1	4.4566 0
3000	1.3868 -5	1.2218 -1	3.0549 0
3100	2.5882 -5	1.3709 -1	2.1478 0
3200	4.6559 -5	1.5311 -1	1.5453 0
3300	8.0724 -5	1.6943 -1	1.1324 0
3400	1.3552 -4	1.8664 -1	8.4918 -1
3500	2.2080 -4	2.0417 -1	6.4565 -1
3600	3.5075 -4	2.2233 -1	4.9888 -1
3700	5.4325 -4	2.4099 -1	3.9084 -1
3800	8.2035 -4	2.6002 -1	3.1046 -1
3900	1.2162 -3	2.7925 -1	2.4946 -1
4000	1.7701 -3	2.9923 -1	2.0324 -1
4100	2.5235 -3	3.1915 -1	1.6672 -1
4200	3.5481 -3	3.3884 -1	1.3868 -1
4300	4.8978 -3	3.5975 -1	1.1588 -1
4400	6.6681 -3	3.8019 -1	9.7949 -2
4500	8.9743 -3	4.0087	8.3368 -2
4600	1.1912 -2	4.2170 -1	7.1285 -2
4700	1.5596 -2	4.4259 -1	6.1518 -2
4800	2.0230 -2	4.6452 -1	5.3456 -2
4900	2.6002 -2	4.8529 -1	4.6774 -2
5000	3.3037 -2	5.0582 -1	4.1115 -2
5100	4.1591 -2	5.2723 -1	3.6308 -2
5200	5.2000 -2	5.4828 -1	3.2211 -2
5300	6.4417 -2	5.6885 -1	2.8774 -2
5400	7.9068 -2	5.9020 -1	2.5763 -2
5500	9.6383 -2	6.1094 -1	2.3174 -2
5600	1.1695 -1	6.3241 -1	2.0941 -2
5700	1.4060 -1	6.5313 -1	1.8967 -2
5800	1.6827 -1	6.7298 -1	1.7258 -2
5900	2.0045 -1	6.9343 -1	1.5776 -2
6000	2.3714 -1	7.1285 -1	1.4471 -2

TABLE 6 REDUCED ABSOLUTE FORMATION ENTHALPIES

$$\left[\frac{\Delta H_{f,abs}}{\mathcal{R}T}\right]_i^T = \left[\frac{\Delta E_{o,f}}{\mathcal{R}}\right]_i^{T\ ^\circ K} \cdot \frac{1}{T} + \left[\frac{H - E_o}{T}\right]_i^T$$

T (K)	H	O	OH	H_2O
100	262.3700	299.5070	50.3910	-283.4050
200	132.4100	151.1550	27.1010	-139.8410
298.16	89.6411	102.2756	19.3815	-92.3808
300	89.1067	101.6640	19.2883	-91.9587
400	67.4550	76.8995	15.3575	-67.8240
500	54.4640	62.0330	12.9970	-53.4850
600	45.8033	52.1190	11.4227	-43.8033
700	39.6171	45.0351	10.2496	-36.9124
800	34.9775	39.7273	9.4598	-31.9210
900	31.3589	35.5893	8.8104	-27.8779
1000	28.4820	32.2820	8.2960	-24.4280
1100	26.1200	29.5754	7.8800	-21.7486
1200	24.1517	27.3205	7.5368	-19.4987
1300	22.4862	25.4116	7.2522	-17.5856
1400	21.0586	23.7756	7.0113	-15.9827
1500	19.8213	22.3580	6.8057	-14.5063
1600	18.7388	21.1171	6.6299	-13.2460
1700	17.7835	20.0228	6.4770	-12.1215
1800	16.9344	19.0497	6.3622	-11.1194
1900	16.1747	18.1787	6.2255	-10.2172
2000	15.4910	17.3945	6.1225	-9.4010
2100	14.8724	16.6857	6.0302	-8.6588
2200	14.3100	16.0412	5.9480	-7.9808
2300	13.7965	15.4525	5.8736	-7.3409
2400	13.3258	14.9128	5.8069	-6.7863
2500	12.8928	14.4170	5.7470	-6.2564
2600	12.4931	13.9593	5.6920	-5.7633
2700	12.1230	13.5354	5.6425	-5.3100
2800	11.7793	13.1418	5.5976	-4.8849
2900	11.4593	12.7752	5.5561	-4.4880
3000	11.1607	12.4330	5.5173	-4.1157
3100	10.8813	12.1128	5.4821	-3.7667
3200	10.6194	11.8135	5.4499	-3.4380
3300	10.3733	11.5325	5.4197	-3.1279
3400	10.1418	11.2669	5.3920	-2.8358
3500	9.9234	11.0174	5.3667	-2.5593
3600	9.7172	10.7818	5.3426	-2.2972
3700	9.5222	10.5560	5.3195	-2.0495
3800	9.3374	10.3468	5.2993	-1.8131
3900	9.1621	10.1485	5.2797	-1.5892
4000	8.9955	9.9593	5.2618	-1.3750
4100	8.8371	9.7782	5.2442	-1.1718
4200	8.6862	9.6069	5.2281	-0.9769
4300	8.5423	9.4434	5.2132	-0.7908
4400	8.4050	9.2876	5.1995	-0.6129
4500	8.2738	9.1387	5.1859	-0.4428
4600	8.1483	8.9963	5.1733	-0.2800
4700	8.0281	8.8610	5.1617	-0.1230
4800	7.9129	8.7304	5.1500	0.0273
4900	7.8024	8.6052	5.1401	0.1725
5000	7.6964	8.4860	5.1300	0.3168
5100	7.5945	8.3706	5.1207	0.4455
5200	7.4965	8.2607	5.1120	0.5738
5300	7.4023	8.1539	5.1031	0.6921
5400	7.3115	8.0522	5.0957	0.8145
5500	7.2240	7.9543	5.0880	0.9343
5600	7.1396	7.8599	5.0808	1.0466
5700	7.0582	7.7679	5.0741	1.1966
5800	6.9797	7.6801	5.0700	1.2595
5900	6.9037	7.5954	5.0624	1.3165
6000	6.8303	7.5135	5.0562	1.4547
$\left(\frac{\Delta E_{o,f}}{\mathcal{R}}\right)$	[illegible]	[illegible]	4675	[illegible]

TABLE 7 REDUCED ABSOLUTE FORMATION ENTHALPIES

$$\left[\frac{\Delta H_{f,abs}}{\mathcal{R}\,T}\right]_i^T = \left[\frac{\Delta E_{o,f}}{\mathcal{R}}\right]_i^{T\ \mathrm{^oK}} \cdot \frac{1}{T} + \left[\frac{H - E_o}{T}\right]_i^T$$

T (K)	NO	N	CO	CO2
100	111.7440	568.6300	-133.3930	-469.3690
200	57.7490	285.6150	-64.9440	-232.862
298.16	39.9789	195.3746	-42.4092	-154.8237
300	38.7037	191.2100	-42.1297	-153.8690
400	30.6765	144.0325	-30.7190	-114.1840
500	25.2670	155.7260	-23.8640	-90.3400
600	21.6743	96.8550	-19.2833	-74.3440
700	19.1211	83.3757	-15.9793	-62.8904
800	17.2178	73.2663	-13.5250	-54.2695
900	15.7469	65.4033	-11.5919	-47.9410
1000	14.5780	59.1130	-10.0370	-42.1420
1100	13.6273	53.9664	-8.7586	-37.7203
1200	12.6392	49.6715	-7.6867	-34.0620
1300	12.1759	46.0485	-6.7792	-30.8668
1400	11.6106	42.9379	-5.9961	-28.1687
1500	11.1223	40.2420	-5.3153	-25.8250
1600	10.6974	37.8831	-4.7170	-23.7698
1700	10.3233	35.8018	-4.1878	-21.9533
1800	9.9924	33.9517	-3.7164	-20.3350
1900	9.6967	32.2963	-3.2922	-18.8534
2000	9.4315	30.8065	-2.9110	-17.5800
2100	9.1934	29.4586	-2.5641	-16.3971
2200	8.9767	28.2332	-2.2478	-15.3195
2300	8.7792	27.1143	-1.9593	-14.3341
2400	8.5986	26.0888	-1.6933	-13.4305
2500	8.4336	25.1452	-1.4492	-12.5934
2600	8.2815	24.2752	-1.2226	-11.8239
2700	8.1406	23.4688	-1.0126	-11.1153
2800	8.0098	22.7199	-0.8176	-10.4529
2900	7.8888	22.0237	-0.6350	-9.8355
3000	7.7757	21.3730	-0.4647	-9.2550
3100	7.6705	20.7653	-0.3055	-8.7175
3200	7.5717	20.1956	-0.1555	-8.2109
3300	7.4794	19.6605	-0.0149	-7.7341
3400	7.3922	19.2109	0.1181	-7.2816
3500	7.3114	18.6831	0.2431	-6.8613
3600	7.2337	18.2348	0.3618	-6.4610
3700	7.1616	17.8118	0.4745	-6.0820
3800	7.0928	17.4112	0.5809	-5.7237
3900	7.0270	17.0312	0.6823	-5.3806
4000	6.9658	16.6713	0.7780	-5.0565
4100	6.9069	16.3280	0.8705	-4.7472
4200	6.8512	16.0023	0.9650	-4.4526
4300	6.7984	15.6928	1.0407	-4.1727
4400	6.7473	15.3966	1.1211	-3.9028
4500	6.6988	15.1147	1.1972	-3.6450
4600	6.6526	14.8452	1.2703	-3.4055
4700	6.6087	14.5883	1.3407	-3.1649
4800	6.5668	14.3414	1.4083	-2.9393
4900	6.5269	14.1057	1.4725	-2.7222
5000	6.4876	13.8796	1.5344	-2.5132
5100	6.4505	13.6636	1.5941	-2.3128
5200	6.4157	13.4551	1.6517	-2.1205
5300	6.3725	13.2557	1.7074	-1.9359
5400	6.3478	13.0649	1.7602	-1.7547
5500	6.3165	12.8803	1.8123	-1.5844
5600	6.2854	12.7035	1.8617	-1.4159
5700	6.2556	12.5321	1.9096	-1.2559
5800	6.2289	12.3779	1.9570	-1.0974
5900	6.2013	12.2094	2.0020	-0.9475
6000	6.1748	12.0575	2.0457	-0.8020
$\left(\frac{\Delta E_{o,f}}{\mathcal{R}}\right)$	10799	56613	-13868	-47206

TABLE 8 REDUCED SENSIBLE ENTHALPIES, $\left[\frac{H - E_o}{\mathcal{R} T}\right]_i^T$

T (K)	N_2	H	O_2	O	OH	H_2O
100	3.820	2.500	3.495	2.657	3.648	3.955
200	3.487	2.500	3.497	2.730	3.720	3.983
298.16	3.418	2.500	3.504	2.715	3.702	3.997
300	3.417	2.500	3.502	2.714	3.699	3.996
400	3.436	2.500	3.521	2.687	3.670	4.016
500	3.452	2.500	3.553	2.663	3.647	4.047
600	3.464	2.500	3.594	2.644	3.631	4.090
700	3.474	2.500	3.640	2.628	3.621	4.139
800	3.484	2.500	3.687	2.610	3.616	4.199
900	3.495	2.500	3.732	2.606	3.616	4.253
1000	3.507	2.500	3.775	2.597	3.621	4.316
1100	3.520	2.500	3.816	2.589	3.630	4.381
1200	3.534	2.500	3.853	2.583	3.641	4.448
1300	3.550	2.500	3.889	2.577	3.656	4.510
1400	3.568	2.500	3.922	2.572	3.672	4.583
1500	3.587	2.500	3.952	2.568	3.689	4.651
1600	3.608	2.500	3.981	2.564	3.708	4.717
1700	3.628	2.500	4.008	2.561	3.727	4.782
1800	3.650	2.500	4.034	2.558	3.746	4.845
1900	3.671	2.500	4.056	2.555	3.765	4.907
2000	3.692	2.500	4.082	2.552	3.785	4.967
2100	3.714	2.500	4.105	2.550	3.804	5.025
2200	3.736	2.500	4.127	2.548	3.823	5.081
2300	3.757	2.500	4.148	2.546	3.841	5.135
2400	3.778	2.500	4.168	2.544	3.859	5.187
2500	3.799	2.500	4.188	2.543	3.877	5.238
2600	3.819	2.500	4.208	2.542	3.894	5.286
2700	3.839	2.500	4.227	2.541	3.911	5.333
2800	3.859	2.500	4.245	2.540	3.928	5.378
2900	3.878	2.500	4.263	2.539	3.944	5.421
3000	3.897	2.500	4.281	2.538	3.959	5.463
3100	3.916	2.500	4.298	2.537	3.974	5.503
3200	3.934	2.500	4.315	2.537	3.989	5.542
3300	3.952	2.500	4.332	2.537	4.003	5.580
3400	3.969	2.500	4.348	2.536	4.017	5.616
3500	3.987	2.500	4.364	2.536	4.031	5.651
3600	4.003	2.500	4.379	2.536	4.044	5.685
3700	4.020	2.500	4.395	2.537	4.056	5.717
3800	4.037	2.500	4.409	2.537	4.069	5.749
3900	4.053	2.500	4.424	2.537	4.081	5.779
4000	4.069	2.500	4.438	2.538	4.093	5.809
4100	4.084	2.500	4.452	2.539	4.104	5.837
4200	4.100	2.500	4.465	2.539	4.115	5.855
4300	4.115	2.500	4.479	2.540	4.126	5.892
4400	4.130	2.500	4.491	2.541	4.137	5.918
4500	4.145	2.500	4.504	2.542	4.147	5.943
4600	4.160	2.500	4.516	2.543	4.157	5.967
4700	4.174	2.500	4.528	2.545	4.167	5.991
4800	4.188	2.500	4.540	2.546	4.176	6.014
4900	4.202	2.500	4.551	2.547	4.186	6.037
5000	4.216	2.500	4.562	2.549	4.195	6.058
5100	4.230	2.500	4.573	2.550	4.204	6.080
5200	4.243	2.500	4.584	2.552	4.213	6.100
5300	4.257	2.500	4.594	2.553	4.221	6.120
5400	4.270	2.500	4.604	2.555	4.230	6.140
5500	4.283	2.500	4.614	2.557	4.238	6.159
5600	4.296	2.500	4.624	2.558	4.246	6.178
5700	4.309	2.500	4.633	2.560	4.254	6.196
5800	4.321	2.500	4.642	2.562	4.262	6.214
5900	4.334	2.500	4.651	2.564	4.270	6.231
6000	4.346	2.500	4.659	2.566	4.277	6.248

$$\left(\frac{H - E_o}{\mathcal{R}T}\right)_i^T = \left(\frac{H - E_o}{\mathcal{R}T}\right)_i^{T_1} + \frac{T - T_1}{100}\left[\left(\frac{H - E_o}{\mathcal{R}T}\right)_i^{T_2} - \left(\frac{H - E_o}{\mathcal{R}T}\right)_i^{T_1}\right]$$

$$T_1 < T < T_1 + 100 = T_2$$

TABLE 9 REDUCED SENSIBLE ENTHALPIES, $\left[\frac{H - E_o}{\mathcal{R}\,T}\right]_i^T$

T (K)	N_2	NO	N	CO	CO_2
100	3.487	3.754	2.501	3.487	3.49[illegible]
200	3.495	3.754	2.499	3.495	3.5[illegible]
298.16	3.499	3.710	2.501	3.499	3.779
300	3.497	3.707	2.499	3.497	3.782
400	3.500	3.679	2.500	3.501	4.021
500	3.508	3.669	2.500	3.512	4.25[illegible]
600	3.520	3.676	2.500	3.530	4.46[illegible]
700	3.541	3.694	2.500	3.555	4.662
800	3.565	3.719	2.500	3.585	4.838
900	3.594	3.748	2.500	3.617	4.999
1000	3.624	3.779	2.500	3.651	5.144
1100	3.655	3.810	2.500	3.685	5.277
1200	3.686	3.840	2.500	3.718	5.397
1300	3.717	3.869	2.500	3.750	5.507
1400	3.746	3.897	2.500	3.781	5.607
1500	3.775	3.923	2.500	3.810	5.699
1600	3.802	3.948	2.500	3.836	5.784
1700	3.828	3.971	2.500	3.864	5.862
1800	3.852	3.993	2.500	3.888	5.934
1900	3.875	4.013	2.500	3.912	6.001
2000	3.898	4.032	2.500	3.933	6.063
2100	3.918	4.051	2.500	3.954	6.120
2200	3.938	4.068	2.500	3.974	6.174
2300	3.957	4.084	2.500	3.992	6.225
2400	3.975	4.099	2.500	4.010	6.272
2500	3.992	4.114	2.500	4.026	6.316
2600	4.008	4.128	2.501	4.042	6.358
2700	4.024	4.141	2.501	4.057	6.398
2800	4.038	4.153	2.501	4.071	6.435
2900	4.052	4.165	2.502	4.085	6.470
3000	4.066	4.176	2.502	4.098	6.504
3100	4.078	4.187	2.503	4.110	6.536
3200	4.090	4.197	2.504	4.122	6.566
3300	4.102	4.207	2.505	4.133	6.595
3400	4.113	4.216	2.506	4.144	6.623
3500	4.124	4.226	2.508	4.154	6.649
3600	4.134	4.234	2.509	4.164	6.674
3700	4.144	4.243	2.511	4.174	6.69[illegible]
3800	4.154	4.251	2.513	4.183	6.722
3900	4.163	4.258	2.515	4.192	6.744
4000	4.172	4.266	2.518	4.200	6.765
4100	4.180	4.273	2.520	4.209	6.78[illegible]
4200	4.189	4.280	2.523	4.217	6.80[illegible]
4300	4.197	4.287	2.527	4.224	6.8[illegible]5
4400	4.204	4.293	2.530	4.232	6.844
4500	4.212	4.299	2.534	4.239	6.862
4600	4.219	4.305	2.538	4.246	6.879
4700	4.226	4.311	2.543	4.253	6.89[illegible]
4800	4.233	4.317	2.547	4.260	6.912
4900	4.240	4.323	2.552	4.266	6.92[illegible]
5000	4.246	4.328	2.557	4.272	6.944
5100	4.253	4.333	2.563	4.278	6.959
5200	4.259	4.339	2.568	4.284	6.973
5300	4.265	4.335	2.574	4.290	6.98[illegible]
5400	4.271	4.348	2.581	4.295	7.00[illegible]
5500	4.276	4.353	2.587	4.301	7.015
5600	4.282	4.358	2.594	4.306	7.0[illegible]
5700	4.288	4.362	2.600	4.311	7.042
5800	4.293	4.367	2.607	4.317	7.054
5900	4.298	4.371	2.614	4.322	7.0[illegible]
6000	4.303	4.375	2.622	4.327	7.079

$$\left(\frac{H - E_0}{\mathcal{R}T}\right)_i^T = \left(\frac{H - E_0}{\mathcal{R}T}\right)_i^{T_1} + \frac{T - T_1}{100}\left[\left(\frac{H - E_0}{\mathcal{R}T}\right)_i^{T_2} - \left(\frac{H - E_0}{\mathcal{R}T}\right)_i^{T_1}\right]$$

$$T_1 < T < T_1 + 100 = T_2$$

TABLE 10 REDUCED ENTROPIES , $\left[\frac{S^{p=1}}{\mathcal{R}}\right]_i^T$

T (K)	H_2	H	O_2	O	OH	H_2O
100	12.272	11.053	20.894	16.337	18.041	18.315
200	14.351	12.735	23.205	18.286	20.642	21.002
298.16	15.704	13.784	24.659	19.357	22.100	22.608
300	15.726	13.799	24.681	19.374	22.122	22.727
400	16.730	14.518	25.709	20.124	23.150	23.844
500	17.515	15.077	26.530	20.697	23.964	24.825
600	18.157	15.532	27.222	21.162	24.590	25.609
700	18.702	15.917	27.826	21.553	25.138	26.292
800	19.176	16.252	28.361	21.840	25.616	26.903
900	19.598	16.546	28.844	22.187	26.042	27.440
1000	19.978	16.809	29.283	22.453	26.428	27.974
1100	20.326	17.048	29.685	22.692	26.752	28.454
1200	20.648	17.265	30.056	22.910	27.110	28.905
1300	20.947	17.465	30.401	23.111	27.416	29.331
1400	21.229	17.650	30.723	23.297	27.704	29.735
1500	21.495	17.823	31.026	23.471	27.975	30.121
1600	21.747	17.984	31.310	23.632	28.232	30.490
1700	21.988	18.136	31.560	23.784	28.476	30.843
1800	22.217	18.279	31.835	23.927	28.709	31.181
1900	22.436	18.414	32.079	24.063	28.932	31.507
2000	22.646	18.542	32.311	24.191	29.145	31.820
2100	22.849	18.664	32.533	24.313	29.349	32.122
2200	23.043	18.781	32.747	24.430	29.545	32.412
2300	23.231	18.891	32.951	24.541	29.734	32.694
2400	23.413	18.998	33.149	24.648	29.916	32.965
2500	23.588	19.100	33.339	24.760	30.092	33.229
2600	23.758	19.198	33.524	24.849	30.261	33.484
2700	23.922	19.292	33.702	24.943	30.425	33.731
2800	24.082	19.383	33.874	25.035	30.584	33.970
2900	24.237	19.471	34.042	25.123	30.738	34.203
3000	24.388	19.556	34.204	25.209	30.888	34.430
3100	24.534	19.638	34.362	25.291	31.033	34.650
3200	24.677	19.717	34.516	25.371	31.174	34.864
3300	24.817	19.794	34.665	25.449	31.311	35.072
3400	24.952	19.869	34.811	25.525	31.444	35.276
3500	25.085	19.941	34.953	25.598	31.575	35.474
3600	25.214	20.011	35.092	25.670	31.701	35.668
3700	25.341	20.080	35.227	25.739	31.825	35.856
3800	25.465	20.147	35.360	25.807	31.945	36.041
3900	25.586	20.212	35.489	25.873	32.063	36.221
4000	25.705	20.275	35.615	25.938	32.178	36.397
4100	25.821	20.337	35.739	26.002	32.291	36.569
4200	25.935	20.397	35.859	26.064	32.401	36.738
4300	26.047	20.456	35.978	26.124	32.509	36.903
4400	26.157	20.513	36.094	26.183	32.614	37.065
4500	26.264	20.570	36.208	26.242	32.717	37.224
4600	26.370	20.624	36.319	26.299	32.819	37.379
4700	26.475	20.678	36.429	26.354	32.918	37.531
4800	26.577	20.731	36.536	26.409	33.015	37.681
4900	26.677	20.782	36.640	26.463	33.111	37.827
5000	26.776	20.833	36.744	26.516	33.205	37.971
5100	26.874	20.883	36.845	26.568	33.297	38.113
5200	26.969	20.931	36.944	26.619	33.387	38.252
5300	27.064	20.979	37.042	26.669	33.476	38.388
5400	27.156	21.025	37.138	26.719	33.563	38.522
5500	27.248	21.071	37.233	26.768	33.649	38.654
5600	27.338	21.116	37.325	26.815	33.733	38.784
5700	27.427	21.160	37.416	26.863	33.816	38.911
5800	27.515	21.204	37.506	26.909	33.898	39.037
5900	27.601	21.247	37.594	26.954	33.978	39.160
6000	27.686	21.289	37.682	26.999	34.057	39.283

TABLE 11 REDUCED ENTROPIES, $\left[\frac{S^{p=1}}{\mathcal{R}}\right]_i^T$

T (K)	N_2	NO	N	CO	CO_2
100	19.179	21.279	15.693	19.885	21.777
200	21.631	23.891	17.427	22.355	24.057
298.16	23.032	25.335	18.424	23.758	25.700
300	23.053	25.354	18.440	23.780	25.727
400	24.062	26.390	19.159	24.790	27.088
500	24.851	27.200	19.717	25.402	28.241
600	25.505	27.876	20.173	26.243	29.249
700	26.069	28.462	20.558	26.814	30.147
800	26.568	28.983	20.892	27.321	30.958
900	27.018	29.452	21.186	27.777	31.698
1000	27.428	29.879	21.450	28.194	32.378
1100	27.806	30.271	21.688	28.577	33.007
1200	28.157	30.634	21.906	28.932	33.598
1300	28.483	30.971	22.106	29.263	34.138
1400	28.789	31.287	22.291	29.573	34.650
1500	29.077	31.583	22.464	29.864	35.132
1600	29.349	31.861	22.625	30.138	35.588
1700	29.606	32.125	22.777	30.398	36.018
1800	29.850	32.374	22.919	30.644	36.428
1900	30.083	32.611	23.054	30.878	36.817
2000	30.304	32.837	23.183	31.102	37.188
2100	30.515	32.851	23.305	31.314	37.543
2200	30.718	33.258	23.421	31.518	37.883
2300	30.912	33.455	23.532	31.714	38.209
2400	31.099	33.645	23.639	31.902	38.522
2500	31.279	33.827	23.741	32.082	38.824
2600	31.452	34.002	23.839	32.256	39.114
2700	31.619	34.172	23.934	32.424	39.394
2800	31.780	34.335	24.026	32.586	39.393
2900	31.936	34.492	24.114	32.743	39.926
3000	32.087	34.645	24.199	32.895	40.180
3100	32.233	34.793	24.282	33.041	40.426
3200	32.375	34.936	24.362	33.184	40.664
3300	32.513	35.075	24.440	33.322	40.896
3400	32.646	35.211	24.516	33.457	41.120
3500	32.776	35.342	24.590	33.587	41.339
3600	32.903	35.470	24.663	33.714	41.552
3700	33.026	35.594	24.733	33.838	41.759
3800	33.147	35.716	24.802	33.959	41.961
3900	33.264	35.834	24.869	34.076	42.159
4000	33.378	35.949	24.936	34.191	42.351
4100	33.490	36.062	25.001	34.303	42.539
4200	33.599	36.171	25.065	34.413	42.723
4300	33.706	36.279	25.127	34.519	42.902
4400	33.810	36.384	25.189	34.624	43.078
4500	33.912	36.487	25.250	34.727	43.250
4600	34.012	36.588	25.310	34.827	48.451
4700	34.110	36.686	25.369	34.925	43.583
4800	34.206	36.783	25.427	35.021	43.745
4900	34.299	36.877	25.484	35.116	43.904
5000	34.392	36.971	25.541	35.208	44.059
5100	34.482	37.062	25.597	35.299	44.212
5200	34.571	37.151	25.652	35.388	44.362
5300	3 658	37.238	25.707	35.475	44.509
5400	34.744	37.324	25.762	35.561	44.653
5500	34.828	37.409	25.815	35.645	44.796
5600	34.911	37.492	25.869	35.728	44.935
5700	34.992	37.574	25.922	35.810	45.073
5800	35.072	37.654	25.974	35.890	45.209
5900	35.151	37.733	26.026	35.969	45.342
6000	35.228	37.811	26.077	36.046	45.473

TABLE 12 REDUCED SPECIFIC HEATS, $\left[\frac{C_p}{R}\right]_i^T$

T (K)	H_2	H	O_2	O	OH
100	2.724	2.500	3.501	2.851	3.924
200	3.280	2.500	3.503	2.735	3.702
298.16	3.468	2.500	3.533	2.635	3.607
300	3.469	2.500	3.534	2.634	3.606
400	3.510	2.500	3.621	2.584	3.566
500	3.519	2.500	3.739	2.557	3.550
600	3.527	2.500	3.860	2.541	3.551
700	3.541	2.500	3.967	2.531	3.566
800	3.566	2.500	4.058	2.524	3.598
900	3.597	2.500	4.133	2.519	3.640
1000	3.633	2.500	4.195	2.516	3.690
1100	3.674	2.500	4.247	2.513	3.744
1200	3.719	2.500	4.291	2.511	3.799
1300	3.769	2.500	4.330	2.510	3.854
1400	3.825	2.500	4.365	2.508	3.908
1500	3.885	(2.500)	4.397	2.507	3.959
1600	3.937	2.500	4.428	2.507	4.007
1700	3.986	2.500	4.458	2.506	4.053
1800	4.034	2.500	4.487	2.506	4.095
1900	4.080	2.500	4.515	2.505	4.134
2000	4.124	2.500	4.544	2.505	4.170
2100	4.166	2.500	4.571	2.505	4.203
2200	4.206	2.500	4.599	2.506	4.235
2300	4.244	2.500	4.627	2.506	4.263
2400	4.280	2.500	4.654	2.507	4.291
2500	4.315	2.500	4.681	2.508	4.339
2600	4.347	2.500	4.707	2.509	4.339
2700	4.378	2.500	4.733	2.511	4.360
2800	4.407	2.500	4.758	2.513	4.381
2900	4.433	2.500	4.782	2.516	4.400
3000	4.458	2.500	4.806	2.518	4.418
3100	4.484	2.500	4.829	2.521	4.435
3200	4.510	2.500	4.851	2.525	4.452
3300	4.535	2.500	4.872	2.529	4.467
3400	4.560	2.500	4.893	2.533	4.481
3500	4.584	2.500	4.913	2.537	4.495
3600	4.609	2.500	4.931	2.541	4.508
3700	4.632	2.500	4.949	2.546	4.521
3800	4.656	2.500	4.966	2.551	4.533
3900	4.679	2.500	4.982	2.557	4.545
4000	4.701	2.500	4.998	2.562	4.556
4100	4.723	2.500	5.013	2.568	4.566
4200	4.745	2.500	5.026	2.574	4.577
4300	4.767	2.500	5.040	2.580	4.587
4400	4.788	2.500	5.052	2.586	4.596
4500	4.808	2.500	5.063	2.592	4.606
4600	4.828	2.500	5.075	2.598	4.615
4700	4.848	2.500	5.085	2.604	4.624
4800	4.868	2.500	5.094	2.610	4.633
4900	4.887	2.500	5.103	2.616	4.641
5000	4.905	2.500	5.111	2.622	4.649
5100	4.924	2.500	5.119	2.628	4.657
5200	4.943	2.500	5.126	2.634	4.665
5300	4.961	2.500	5.133	2.640	4.673
5400	4.979	2.500	5.139	2.646	4.681
5500	4.997	2.500	5.146	2.652	4.688
5600	5.015	2.500	5.152	2.657	4.695
5700	5.032	2.500	5.157	2.663	4.702
5800	5.049	2.500	5.162	2.668	4.709
5900	5.066	2.500	5.167	2.674	4.716
6000	5.083	2.500	5.171	2.679	4.723

$$\left(\frac{C_p}{R}\right)_i^T = \left(\frac{C_p}{R}\right)_i^{T_1} + \frac{T - T_1}{100}\left[\left(\frac{C_p}{R}\right)_i^{T_2} - \left(\frac{C_p}{R}\right)_i^{T_1}\right]$$

TABLE 13 REDUCED SPECIFIC HEATS, $\left[\frac{C_p}{\mathcal{R}}\right]_i^T$

T (K)	N_2	N	NO	CO_2	CO	H_2O
100	3.500	2.500	3.885	3.513	3.500	4.006
200	3.501	2.500	3.609	3.892	3.501	4.010
298.16	3.503	2.500	3.590	4.466	3.505	4.039
300	3.503	2.500	3.599	4.477	3.505	4.039
400	3.518	2.500	3.602	4.970	3.529	4.119
500	3.557	2.500	3.667	5.367	3.583	4.235
600	3.621	2.500	3.757	5.692	3.661	4.366
700	3.699	2.500	3.852	5.961	3.749	4.505
800	3.780	2.500	3.941	6.186	3.837	4.653
900	3.860	2.500	4.020	6.374	3.918	4.804
1000	3.933	2.500	4.088	6.532	3.991	4.957
1100	3.998	2.500	4.146	6.664	4.055	5.109
1200	4.057	2.500	4.195	6.776	4.110	5.255
1300	4.107	2.500	4.237	6.872	4.158	5.411
1400	4.153	2.500	4.273	6.952	4.200	5.529
1500	4.192	2.500	4.304	7.022	4.230	5.653
1600	4.226	2.500	4.330	7.082	4.257	5.768
1700	4.256	2.500	4.353	7.134	4.295	5.875
1800	4.283	2.500	4.374	7.181	4.319	5.973
1900	4.307	2.501	4.392	7.222	4.341	6.063
2000	4.328	2.501	4.408	7.259	4.360	6.146
2100	4.347	2.501	4.422	7.291	4.377	6.220
2200	4.364	2.502	4.435	7.320	4.392	6.293
2300	4.380	2.502	4.447	7.347	4.406	6.358
2400	4.394	2.504	4.458	7.371	4.419	6.418
2500	4.406	2.505	4.467	7.393	4.430	6.473
2600	4.418	2.507	4.476	7.415	4.441	6.524
2700	4.428	2.510	4.485	7.433	4.451	6.572
2800	4.438	2.513	4.492	7.451	4.460	6.615
2900	4.448	2.517	4.499	7.468	4.468	6.657
3000	4.456	2.522	4.506	7.485	4.476	6.695
3100	4.464	2.527	4.513	7.499	4.484	6.730
3200	4.472	2.534	4.519	7.513	4.491	6.764
3300	4.479	2.541	4.525	7.526	4.497	6.795
3400	4.486	2.550	4.530	7.539	4.503	6.825
3500	4.492	2.559	4.535	7.551	4.509	6.852
3600	4.498	2.570	4.540	7.564	4.515	6.879
3700	4.504	2.582	4.545	7.575	4.521	6.903
3800	4.510	2.595	4.550	7.586	4.526	6.926
3900	4.515	2.608	4.554	7.597	4.531	6.949
4000	4.521	2.623	4.558	7.608	4.536	6.970
4100	4.526	2.639	4.562	7.618	4.541	6.990
4200	4.530	2.656	4.566	7.628	4.546	7.008
4300	4.535	2.674	4.570	7 639	4.550	7.027
4400	4.540	2.693	4.574	7.648	4.555	7.044
4500	4.544	2.712	4.578	7.657	4.559	7.060
4600	4.549	2.733	4.582	7.666	4.563	7.076
4700	4.553	2.754	4.585	7.676	4.567	7.091
4800	4.558	2.776	4.589	7.685	4.571	7.106
4900	4.562	2.799	4.592	7.694	4.575	7.120
5000	4.566	2.822	4.595	7.702	4.579	7.133
5100	4.571	2.846	4.599	7.713	4.583	7.146
5200	4.575	2.870	4.602	7.724	4.587	7.160
5300	4.579	2.894	4.606	7.735	4.591	7.173
5400	4.584	2.919	4.609	7.746	4.594	7.186
5500	4.588	2.944	4.612	7.757	4.599	7.198
5600	4.593	2.969	4.615	7.768	4.602	7.210
5700	4.598	2.994	4.618	7.779	4.606	7.222
5800	4.602	3.019	4.621	7.790	4.610	7.234
5900	4.607	3.045	4.624	7.802	4.613	7.245
6000	4.612	3.070	4.627	7.813	4.617	7.258

$$\left(\frac{C_p}{\mathcal{R}}\right)_i^T = \left(\frac{C_p}{\mathcal{R}}\right)_i^{T_1} + \frac{T - T_1}{100}\left[\left(\frac{C_p}{\mathcal{R}}\right)_i^{T_2} - \left(\frac{C_p}{\mathcal{R}}\right)_i^{T_1}\right]$$

$$T_1 < T < T_1 + 100 = T_2$$

TABLE 14 REDUCED ENTROPY DIVIDED BY ln T, $\left[\dfrac{S^{p=1}/R}{\ln T}\right]_i^T$

T (K)	H_2	H	O_2	O	OH	H_2O
100	2.6648	2.4001	4.5371	3.5475	3.9170	3.9771
200	2.7086	2.4130	4.3910	3.4513	3.8950	3.9809
298.16	2.7562	2.4193	4.3279	3.3974	3.8788	3.9838
300	2.7571	2.4193	4.3271	3.3957	3.8785	3.9838
400	2.7923	2.4231	4.2909	3.3588	3.8638	3.9880
500	2.8184	2.4261	4.2690	3.3304	3.8529	3.9946
600	2.8384	2.4280	4.2555	3.3081	3.8440	4.0033
700	2.8548	2.4297	4.2475	3.2900	3.8372	4.0134
800	2.8687	2.4313	4.2427	3.2747	3.8321	4.0246
900	2.8810	2.4324	4.2403	3.2616	3.8284	4.0368
1000	2.8921	2.4334	4.2391	3.2504	3.8258	4.0497
1100	2.9024	2.4344	4.2389	3.2403	3.8243	4.0631
1200	2.9122	2.4351	4.2392	3.2313	[illegible]	4.0772
1300	2.9214	2.4358	4.2400	3.2232	[illegible]	4.0907
1400	2.9305	2.4364	4.2410	3.2170	3.8243	4.1046
1500	2.9392	2.4371	4.2425	3.2094	3.8253	4.1187
1600	2.9476	2.4376	4.2438	3.2031	3.8266	4.1327
1700	2.9560	2.4382	4.2455	3.1975	3.8283	4.1465
1800	2.9640	2.4386	4.2472	3.1922	3.8301	4.1599
1900	2.9718	2.4391	4.2491	3.1873	3.8323	4.1733
2000	2.9794	2.4394	4.2509	3.1826	3.8344	4.1863
2100	2.9870	2.4398	4.2529	3.1783	3.8366	4.1991
2200	2.9941	2.4403	4.2550	3.1743	3.8389	4.2114
2300	3.0012	2.4405	4.2569	3.1704	3.8413	4.2237
2400	3.0081	2.4409	4.2590	3.1668	3.8437	4.2354
2500	3.0148	2.4412	4.2611	3.1633	3.8461	4.2470
2600	3.0214	2.4415	4.2634	3.1601	3.8484	4.2583
2700	3.0277	2.4417	4.2655	3.1569	3.8508	4.2692
2800	3.0340	2.4420	4.2677	3.1541	3.8532	4.2796
2900	3.0401	2.4423	4.2699	3.1512	3.8555	4.2901
3000	3.0461	2.4426	4.2721	3.1486	3.8579	4.3003
3100	3.0518	2.4428	4.2743	3.1460	3.8602	4.3102
3200	3.0575	2.4430	4.2766	3.1435	3.8625	4.3197
3300	3.0632	2.4432	4.2787	3.1412	3.8648	4.3290
3400	3.0685	2.4435	4.2810	3.1390	3.8669	4.3381
3500	3.0739	2.4436	4.2832	3.1368	3.8692	4.3470
3600	3.0791	2.4437	4.2854	3.1348	3.8713	4.3558
3700	3.0843	2.4440	4.2876	3.1328	3.8735	4.3642
3800	3.0894	2.4442	4.2898	3.1309	3.8755	4.3724
3900	3.0943	2.4444	4.2920	3.1290	3.8776	4.3805
4000	3.0992	2.4445	4.2940	3.1273	3.8796	4.3883
4100	3.1040	2.4447	4.2962	3.1257	3.8817	4.3960
4200	3.1087	2.4449	4.2982	3.1241	3.8837	4.4035
4300	3.1133	2.4450	4.3003	3.1225	3.8857	4.4109
4400	3.1179	2.4451	4.3024	3.1210	3.8875	4.4181
4500	3.1223	2.4454	4.3044	3.1197	3.8894	4.4252
4600	3.1267	2.4454	4.3064	3.1183	3.8914	4.4320
4700	3.1312	2.4456	4.3084	3.1169	3.8932	4.4387
4800	3.1354	2.4457	4.3103	3.1156	3.8949	4.4454
4900	3.1396	2.4458	4.3121	3.1144	3.8958	4.4518
5000	3.1438	2.4460	4.3141	3.1132	3.8986	4.4582
5100	3.1480	2.4462	4.3159	3.1121	3.9003	4.4645
5200	3.1519	2.4462	4.3177	3.1110	3.9020	4.4706
5300	3.1560	2.4464	4.3195	3.1099	3.9037	4.4765
5400	3.1598	2.4464	4.3213	3.1090	3.9053	4.4823
5500	3.1639	2.4466	4.3231	3.1080	3.9070	4.4882
5600	3.1676	2.4467	4.3248	3.1070	3.9086	4.4938
5700	3.1714	2.4467	4.3264	3.1062	3.9102	4.4993
5800	3.1752	2.4469	4.3281	3.1053	3.9118	4.5049
5900	3.1789	2.4470	4.3298	3.1043	3.9133	4.5102
6000	3.1825	2.4472	4.3315	3.1035	3.9144	4.5155

$$\left(\frac{S^{p=1}}{R}\right)_i^T = \ln T\left\{\left[\left(\frac{S^{p=1}/R}{\ln T}\right)\right]_i^{T_1} + \frac{T-T_1}{100}\left(\left[\left(\frac{S^{p=1}/R}{\ln T}\right)\right]_i^{T_2} - \left[\left(\frac{S^{p=1}/R}{\ln T}\right)\right]_i^{T_1}\right)\right\}$$

$$T_1 < T < T_1 + 100 = T_2$$

TABLE 15 REDUCED ENTROPY DIVIDED BY ln T, $\left[\dfrac{S^{p=1}/\mathcal{R}}{\ln T}\right]_i^T$

T (K)	N_2	NO	N	CO	CO_2
100	4.1647	4.6207	3.4077	4.3180	4.7288
200	4.0826	4.5092	3.2892	4.2193	4.5405
298.16	4.0424	4.4466	3.2336	4.1698	4.5106
300	4.0417	4.4458	3.2329	4.1692	4.5105
400	4.0160	4.4046	3.1977	4.1376	4.5211
500	3.9988	4.3768	3.1727	4.1160	4.5443
600	3.9871	4.3577	3.1535	4.1024	4.5723
700	3.9793	4.3446	3.1381	4.0931	4.6015
800	3.9745	4.3358	3.1254	4.0871	3.6312
900	3.9718	4.3297	3.1145	4.0834	4.6596
1000	3.9706	4.3254	3.1052	4.0815	4.6872
1100	3.9705	4.3225	3.0969	4.0806	4.7132
1200	3.9713	4.3207	3.0897	4.0806	4.7379
1300	3.9725	4.3195	3.0831	4.0812	4.7611
1400	3.9741	4.3189	3.0771	4.0823	4.7831
1500	3.9760	4.3186	3.0717	4.0836	4.8039
1600	3.9780	4.3185	3.0666	4.0850	4.8237
1700	3.9802	4.3188	3.0621	4.0866	4.8422
1800	3.9824	4.3191	3.0577	4.0883	4.8600
1900	3.9847	4.3196	3.0537	4.0900	4.8767
2000	3.9869	4.3201	3.0500	4.0919	4.8926
2100	3.9890	4.3207	3.0465	4.0935	4.9078
2200	3.9913	4.3213	3.0432	4.0953	4.9223
2300	3.9935	4.3220	3.0400	4.0971	4.9361
2400	3.9956	4.3228	3.0372	4.0988	4.9494
2500	3.9978	4.3235	3.0344	4.1004	4.9621
2600	3.9997	4.3242	3.0317	4.1021	4.9743
2700	4.0019	4.3250	3.0292	4.1038	4.9859
2800	4.0038	4.3257	3.0269	4.1054	4.9971
2900	4.0058	4.3263	3.0247	4.1070	5.0080
3000	4.0077	4.3272	3.0225	4.1086	5.0185
3100	4.0095	4.3279	3.0205	4.1100	5.0286
3200	4.0113	4.3286	3.0185	4.1116	5.0383
3300	4.0131	4.3294	3.0167	4.1130	5.0478
3400	4.0147	4.3302	3.0149	4.1145	5.0569
3900	4.0164	4.3309	3.0133	4.1158	5.0657
3600	4.0181	4.3316	3.0118	4.1171	5.0743
3700	4.0197	4.3322	3.0103	4.1185	5.0826
3800	4.0213	4.3330	3.0089	4.1199	5.0907
3900	4.0229	4.3337	3.0076	4.1211	5.0986
4000	4.0243	4.3343	3.0065	4.1224	5.1062
4100	4.0258	4.3350	3.0054	4.1236	5.1136
4200	4.0273	4.3356	3.0044	4.1249	5.1209
4300	4.0287	4.3363	3.0033	4.1259	5.1279
4400	4.0301	4.3369	3.0025	4.1271	5.1348
4500	4.0314	4.3376	3.0017	4.1284	5.1416
4600	4.0328	4.3383	3.0010	4.1294	5.1484
4700	4.0341	4.3388	3.0004	4.1305	5.1545
4800	4.0355	4.3395	2.9998	4.1316	5.1608
4900	4.0366	4.3400	2.9992	4.1328	5.1670
5000	4.0379	4.3407	2.9988	4.1338	5.1729
5100	4.0391	4.3413	2.9984	4.1348	5.1789
5200	4.0404	4.3419	2.9980	4.1358	5.1846
5300	4.0415	4.3424	2.9977	4.1368	5.1903
5400	4.0427	4.3430	2.9976	4.1378	5.1957
5500	4.0439	4.3436	2.9974	4.1308	5.2013
5600	4.0451	4.3441	2.9974	4.1397	5.2066
5700	4.0461	4.3447	2.9474	4.1407	5.2118
5800	4.0473	4.3452	2.9974	4.1417	5.2160
5900	4.0484	4.3458	2.9975	4.1426	5.2271
6000	4.0494	4.3463	2.9975	4.1434	5.2271

$$\left(\frac{S^{p=1}}{\mathcal{R}}\right)_i^T = \ln T\left\{\left[\frac{\left(\frac{S^{p=1}}{\mathcal{R}}\right)}{\ln T}\right]_i^{T_1} + \frac{T-T_1}{100}\left(\left[\frac{\left(\frac{S^{p=1}}{\mathcal{R}}\right)}{\ln T}\right]_i^{T_2} - \left[\frac{\left(\frac{S^{p=1}}{\mathcal{R}}\right)}{\ln T}\right]_i^{T_1}\right)\right\}$$

$$T_1 < T < T_1 + 100 = T_2$$

TABLE 16

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET
SHOCKED INLET (CRITICAL CONDITION)

	FREE STREAM ∞	FUSELAGE AIRSTREAM 1	DIFFUSER INLET 2	DIFFUSER THROAT 3
T (K)	200	230	1256.6	1110.5
P (atm)	.01	.02	.59236	.3565
u (m/s)	1420.3	1525	281.315	652.274
M (frozen)	5	5	0.407	1.000
η_{O_2}	.210084	.210084	.209922	.210032
η_{N_2}	.789916	.789916	.789752	.789864
η_{O}	0	0	0	0
η_{N}	0	0	0	0
η_{NO}	0	0	.000326	.000104
η_{H_2}	0	0	0	0
η_{H_2O}	0	0	0	0
η_{OH}	0	0	0	0
η_{H}	0	0	0	0
$\mathcal{M}$ (g/mole)	28.853	28.853	28.853	28.853
γ (frozen)	1.4	1.4	1.319167	1.32772
$\frac{S}{R_2}$	NC	NC	29.7868	29.7862
$\frac{h^T_{f\ abs}}{R_2 T_2}$	NC	.556455	3.742178	3.263834
$\frac{A}{A_3}$	NA	NA	1.5782	1

NC-means Not Calculated
NA-means Not Applicable

TABLE 17

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET

SHOCKED INLET, $M_1=5$, $\nu^{\circ}_{O_2} = 0.5$

	DIFFUSER EXIT 3c	COMBUSTION CHAMBER INLET 3c	COMBUSTION CHAMBER EXIT 4	EXHAUST NOZZLE EXIT 5
T (K)	739	739	2428	2123
P (atm)	.0722	.0722	.0722	.02
u (m/s)	1125.78	1125.78	1125.78	1813.105
M (frozen)	2.093	NC	1.088	1.896
n_{O_2}	.210084	.147929	.0129	.0071
n_{N_2}	.789916	.556213	.627008	.642571
n_O	0	0	.004220	.000964
n_{NO}	0	0	.004694	.001853
n_{H_2}	0	.295858	.038280	.018524
n_{H_2O}	0	0	.280390	.318257
n_{OH}	0	0	.019017	.0075696
n_H	0	0	.013169	.003441
$\mathcal{M}$ (g/mole)	28.853	NC	23.652848	24.203772
γ (frozen)	1.358717	NC	1.254343	1.253704
$\frac{S}{R_2}$	29.7868	NC	42.50791	42.5074
$\frac{h^T_{f\ abs}}{R_2 T_2}$	2.101288	NC	2.876558	.087128
$\frac{A}{A_3}$	1.9028	1.9028	7.6261	14.6064

TABLE 18

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET
SHOCKED INLET, M =5, $\mathcal{J}^{o}_{O_2}$ =2

	DIFFUSER EXIT 3c	COMBUSTION CHAMBER INLET 3c	COMBUSTION CHAMBER EXIT 4	EXHAUST NOZZLE EXIT 5
T (K)	967	967	1656.7	931
P(atm)	.205	.205	.205	.02
u (m/s)	870.529	870.529	870.529	1623.397
M (frozen)	1.426	NC	1.085	2.717
n_{O_2}	.210084	.190114	.1486	.1497
n_{N_2}	.789916	.714829	.749335	.750492
n_{O}	0	0	.000024	0
n_{N}	0	NC	NC	NC
n_{NO}	0	0	.002161	.000018
n_{H_2}	0	.095057	.000007	0
n_{H_2O}	0	0	.099592	.099800
n_{OH}	0	0	.000379	0
n_{H}	0	0	.0000006	0
$\mathcal{M}$(g/mole)	28.853	NC	27.614528	27.614592
γ (frozen)	1.3373	NC	1.291421	1.330458
$\frac{S}{R_2}$	29.7840	NC	33.5544	33.5550
$\frac{h^T_{f\ abs}}{R_2 T_2}$	2.804904	NC	3.065934	.473109
$\frac{A}{A_3}$	1.1340	1.1340	2.0300	6.2703

TABLE 19

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET SHOCKED INLET (CRITICAL CONDITION)

	FREE STREAM ∞	FUSELAGE AIRSTREAM 1	DIFFUSER INLET 2	DIFFUSER THROAT 3
T (K)	200	300	3084	2835
P (atm)	.01	.04	3.162	1.046
u (m/s)	2840.5	2785	368.434	1014.94
M (frozen)	10	8	0.341	0.986
n_{O_2}	.210084	.210084	.16568	.17679
n_{N_2}	.789916	.789916	.752654	.761866
n_O	0	0	.034057	.024984
n_N	0	0	.000011	.000004
n_{NO}	0	0	.047598	.036356
n_{H_2}	0	0	0	0
n_{H_2O}	0	0	0	0
n_{OH}	0	0	0	0
n_H	0	0	0	0
$\mathcal{M}$ (g/mole)	28.853	28.853	28.36149	28.490545
γ (frozen)	1.4	1.4	1.289101	1.249
$\frac{S}{R_2}$	NC	NC	32.6595	32.6564
$\frac{h_{f\ abs}^{T}}{R_2 T_2}$	NC	.340277	4.55986	4.065243
$\frac{A}{A_3}$	NA	NA	.9958	1

TABLE 20

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET

SHOCKED INLET, M =10, $\nu^{o}_{O_2}$ =0.5

	DIFFUSER EXIT 3c	COMBUSTION CHAMBER INLET 3c	COMBUSTION CHAMBER EXIT 4	EXHAUST NOZZLE EXIT 5
T (K)	2490	2490	3026.5	2223
P (atm)	.46	.46	.46	.04
u (m/s)	1514.986	1514.986	1514.986	3134.385
M (frozen)	1.571	NC	1.247	3.198
n_{O_2}	.193418	.147929	.0222	.0082
n_{N_2}	.775113	.556213	.570000	.639646
n_{O}	.008879	0	.027032	.001414
n_{N}	.0000004	0	NC	NC
n_{NO}	.022589	0	.014186	.002508
n_{H_2}	0	.295858	.075977	.022755
n_{H_2O}	0	0	.171442	.310772
n_{OH}	0	0	.049762	.009909
n_{H}	0	0	.069330	.004846
$\mathcal{M}$ (g/mole)	28.72488	NC	21.695834	24.09626
γ (frozen)	1.290383	NC	1.273074	1.252743
$\frac{S}{R_2}$	32.6600	NC	41.36155	41.38221
$\frac{h^{T}_{f\ abs}}{R_2 T_2}$	3.365602	NC	4.500086	0.336135
$\frac{A}{A_3}$	1.3901	1.3901	2.1356	7.8505

TABLE 21

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET

SHOCKED INLET, M =10, $\nu^o_{O_2}$ =2

	DIFFUSER EXIT 3c	COMBUSTION CHAMBER INLET 3c	EXIT 4	EXHAUST NOZZLE EXIT 5
T (K)	2661	2661	2836.5	1839
P (atm)	.7	.7	.7	.04
u (m/s)	1300.023	1300.023	1300.023	2407.716
M (frozen)	1.302	NC	1.225	2.852
n_{O_2}	.186028	.190114	.1162	.14697
n_{N_2}	.769139	.714829	.713782	.747921
n_O	.015643	0	,025328	.000332
n_N	.000001	0	NC	NC
n_{NO}	.029191	0	.028587	.004120
n_{H_2}	0	.095057	.006309	.000099
n_{H_2O}	0	0	.071173	.098709
n_{OH}	0	0	.029890	.001824
n_H	0	0	.008782	.000024
m (g/mole)	28.627296	NC	26.790837	27.59534
γ (frozen)	1.289737	NC	1.280166	1.286426
$\frac{S}{R_2}$	32.64504	NC	35.3137	35.31434
$\frac{h^T_{f\ abs}}{R_2 T_2}$	3.700259	NC	3.79076	1.5194
$\frac{A}{A_3}$	1.0898	1.0898	1.2413	7.3824

TABLE 22

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET
SHOCK EXPELLED (SUPERCRITICAL CONDITION)

	FREE STREAM	FUSELAGE AIRSTREAM 1	DIFFUSER INLET 2	DIFFUSER THROAT 3
T (K)	200	230	230	1107.5
P (atm)	.01	.02	.02	6.28
u (m/s)	1420.3	1525	1525	657.56
M (frozen)	5	5	5	1.0103
n_{O_2}	.210085	.210084	.210084	.210033
n_{N_2}	.789916	.789916	.789916	.789866
n_O	0	0	0	0
n_N	0	0	0	0
n_{NO}	0	0	0	.000101
n_{H_2}	0	0	0	0
n_{H_2O}	0	0	0	0
n_{OH}	0	0	0	0
n_H	0	0	0	0
$\mathcal{M}$ (g/mole)	28.853	28.853	28.853	28.85297
γ (frozen)	1.4	1.4	1.4	1.327386
$\frac{S}{R_2}$	NC	26.907	26.907	26.9061
$\frac{h_{f\ abs}^{T}}{R_2 T_2}$	NC	3.496209	3.496209	17.77895
$\frac{A}{A_3}$	NA	NA	28.1177	1

TABLE 23

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET

SHOCK EXPELLED, M =5, $\nu^{o}_{O_2}$ =0.5

	DIFFUSER EXIT 3c	COMBUSTION CHAMBER INLET 3c	COMBUSTION CHAMBER EXIT 4	EXHAUST NOZZLE EXIT 5
T (K)	754.9	754.9	2604	1234.5
P (atm)	1.395	1.395	1.395	.02
u (m/s)	1110.205	1110.205	1110.205	2356.845
M (frozen)	2.064	NC	1.046	3.215
n_{O_2}	.210084	.147929	.008	.00001
n_{N_2}	.78916	.556213	.635607	.652770
n_O	0	0	.001783	0
n_N	0	0	NC	NC
n_{NO}	0	0	.005034	.000002
n_{H_2}	0	.295858	.027711	.000021
n_{H_2O}	0	0	.301792	.347196
n_{OH}	0	0	.014371	.000002
n_H	0	0	.005478	0
$\mathcal{M}$ (g/mole)	28.853	NC	23.98566	24.543573
γ (frozen)	1.329684	NC	1.247582	1.285460
$\frac{S}{R_2}$	26.90625	NC	38.92074	38.92110
$\frac{h^T_{f\ abs}}{R_2 T_2}$	11.74239	NC	15.928338	-25.9767
$\frac{A}{A_3}$	1.8175	1.8175	7.5414	114.7979

TABLE 24

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET
SHOCK EXPELLED, M =5, $\nu^{o}_{O_2}$ =2

	DIFFUSER EXIT	COMBUSTION CHAMBER INLET	EXIT	EXHAUST NOZZLE EXIT
	3c	3c	4	5
T (K)	936	936	1705	484
P (atm)	3.2	3.2	3.2	.02
u (m/s)	910.123	910.123	910.123	1742.997
M (frozen)	1.515	NC	1.119	3.889
n_{O_2}	.210084	.190114	.14825	.1497
n_{N_2}	.789916	.714829	.749144	.750499
n_O	0	0	.000010	0
n_N	0	0	NC	NC
n_{NO}	0	0	.002600	0
n_{H_2}	0	.095057	.000003	0
n_{H_2O}	0	0	.099657	.099800
n_{OH}	0	0	.000266	0
n_H	0	0	.0000002	0
$\mathcal{M}$(g/mole)	28.853	NC	27.610155	27.613586
γ (frozen)	1.33755	NC	1.289948	1.378425
$\frac{S}{R_2}$	26.9074	NC	30.9574	30.9551
$\frac{h^T_{f\,abs}}{R_2 T_2}$	14.79195	NC	17.73222	-5.186886
$\frac{A}{A_3}$	1.1983	1.1983	2.2811	54.0926

TABLE 25

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET SHOCK EXPELLED (SUPERCRITICAL CONDITION)

	FREE STREAM ∞	FUSELAGE AIRSTREAM 1	DIFFUSER INLET 2	DIFFUSER THROAT 3
T (K)	200	300	300	2940
P(atm)	.01	.04	.04	272
u (m/s)	2840.5	2785	2785	1042.96
M (frozen)	10	8	8	0.999
n_{O_2}	.210084	.210084	.210084	.187123
n_{N_2}	.789916	.789916	.789916	.767460
n_O	0	0	0	.002396
n_N	0	0	0	.0000005
n_{NO}	0	0	0	.043021
n_{H_2}	0	0	0	0
n_{H_2O}	0	0	0	0
n_{OH}	0	0	0	0
n_H	0	0	0	0
m(g/mole)	28.853	28.853	28.853	28.818412
γ (frozen)	1.4	1.4	1.4	1.284703
$\frac{S}{R_2}$	NC	27.5823	27.5823	27.5793
$\frac{h_{f\ abs}^{T}}{R_2 T_2}$	NC	3.49805	3.49805	42.0671
$\frac{A}{A_3}$	NA	NA	259.3541	1

TABLE 26

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET
SHOCK EXPELLED, M =10, $\nu^{\circ}_{O_2}$ =0.5

	DIFFUSER EXIT 3c	COMBUSTION CHAMBER INLET 3c	COMBUSTION CHAMBER EXIT 4	EXHAUST NOZZLE EXIT 5
T (K)	2570	2570	3579.4	729
P (atm)	136	136	136	.04
u (m/s)	1480.836	1480.836	1480.836	3423.661
M (frozen)	1.516	NC	1.176	5.969
n_{O_2}	.19657	.147929	.099	.0000001
n_{N_2}	.776561	.556213	.613449	.652778
n_{O}	.000765	0	.005079	0
n_{N}	0	0	NC	NC
n_{NO}	.026104	0	.017033	0
n_{H_2}	0	.295858	.051814	0
n_{H_2O}	0	.255195	.347222	.347222
n_{OH}	0	0	.033965	0
n_{H}	0	0	.013684	0
$\mathcal{M}$(g/mole)	28.841937	NC	23.389112	24.543781
γ (frozen)	1.288146	NC	1.245256	1.332298
$\frac{S}{R_2}$	27.58286	NC	33.8596	33.85376
$\frac{h^T_{f\,abs}}{R_2 T_2}$	35.67526	NC	39.433868	-28.35987
$\frac{A}{A_3}$	1.2303	1.2303	2.1131	603.1073

TABLE 27

FLUID PROPERTIES OF SUPERSONIC COMBUSTION RAMJET

SHOCK EXPELLED, M =10, $\nu^{o}_{O_2}$ =2

	DIFFUSER EXIT	COMBUSTION CHAMBER INLET	COMBUSTION CHAMBER EXIT	EXHAUST NOZZLE EXIT
	3c	3c	4	5
T (K)	2734	2734	3110	448
P (atm)	186	186	186	.04
u (m/s)	1309.282	1309.282	1309.282	2752.387
M (frozen)	1.300	NC	1.197	6.368
n_{O_2}	.19268	.190114	.1128	.1497
n_{N_2}	.772792	.714829	.724572	.750499
n_{O}	.001331	0	.004156	0
n_{N}	.0000001	0	NC	NC
n_{NO}	.033197	0	.041401	0
n_{H_2}	0	.095057	.001223	0
n_{H_2O}	0	0	.089893	.099800
n_{OH}	0	0	.015420	0
n_{H}	0	0	.000559	0
$\mathcal{M}$(g/mole)	28.83377	NC	27.42287	27.614384
γ (frozen)	1.286661	NC	1.269813	1.385055
$\frac{S}{R_2}$	27.58312	NC	29.94482	29.94014
$\frac{h^{T}_{f\ abs}}{R_2 T_2}$	38.4437	NC	39.38418	-4.431565
$\frac{A}{A_3}$	1.0827	1.0827	1.2950	409.7627

BIBLIOGRAPHY

Edse R., Ignition, Combustion, Detonation, and Quenching of Reactive Mixtures, AFOSR-TR-RF Project 3641, November, 1975

Preyss and Hearth, The Case for a Hypersonic Research Vechile, Astronautics and Aeronautics, December 1976

Sims, Joseph L. Sims, Tables for Supersonic Flow Around Right Circular Cones at Zero Angle of Attack, NASA SP 3004, 1964